Master's Thesis

Color Appearance Study under Two Lightings Having Different Illuminance Levels

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ABSTRACT

Color appearances of the objects are changing, depending on light sources. In everyday life, it is common to see a scene having two or more light sources together, or to look at an object that is shadowed by other objects. However, these situations might not be interpreted by current color appearance models, which are based on a single light source. With increasing interest in color reproduction of high dynamic scenes, color appearance research that can explain these multi illumination situations is necessary.

In this research, it was intended to explain color appearance phenomena in the context where observers alternately saw two light sources having largely different illuminance levels (7005 lux and 376 lux, respectively) being present at the same time. This study also attempted to identify the observer's state of adaptation in the presence of multiple lightings, by exploring how color appearance in terms of hue, brightness and colorfulness changes in complex multiple lighting conditions, as opposed to single lighting conditions.

Psychophysical experiment based on magnitude estimation technique was conducted to estimate color appearance and was composed of four sessions according to 1) illuminance of lighting either high or low, and 2) observer's adaptation to the lighting conditions for either single lighting or multiple lightings. Seven observers who were skillfully trained for color appearance estimation participated in the experiment and evaluated the color appearance of 50 color patches in terms of hue, colorfulness and brightness throughout the four sessions.

As for the analyses of the results, human color perception data regarding hue, brightness and colorfulness of all observers were averaged and compared across sessions, based on the illuminance of lighting and the observer's adaptation to the lighting conditions. Also, the color appearance model CIECAM02 performance was evaluated in terms of hue, brightness and colorfulness by comparing model prediction data with color perception data.

As a result, through the color appearance study under two lightings with different illuminance levels, it turned out that hue appearance was not affected by the illuminance level of lighting and the observer's adaptation to the lighting conditions. Perceived brightness and colorfulness were increased under higher illuminance level, but not affected by the observer's adaptation to the lighting conditions, explaining that observers locally adapted to the lighting where the color was directly shown. It was also found that the CIECAM02 H adeptly predicted hue appearance regardless of the illuminance level of lighting and the observer's adaptation to the lighting conditions. However, the CIECAM02 Q and the CIECAM02 M were overestimated under high illuminance lighting. The modification of the luminance-level

adaptation factor, F_L, by lowering the value from 1.20 to 0.67, helped the model not to overestimate Q and M.

These results are based on color appearance perception when there are only two lightings having 19 times the illuminance difference. Consequently, it cannot be firmly concluded that these phenomena are common color appearance in multiple lighting environments. Therefore, it is necessary to conduct additional color appearance estimation research in multiple lighting conditions having more diverse illuminance level differences or having different configurations of lightings.

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Introduction

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1.1 Research Question

A color appearance model is a mathematical model that explains how a human perceives color, regarding color attributes such as hue, brightness, lightness, colorfulness, chroma, saturation, etc. Human perceives a color of interest differently according to the characteristics of the surrounding condition (color and intensity of lighting; background color; the luminance of the background; colors of nearby objects, etc.). Therefore, measuring only the physical properties of color does not fully explain how color is perceived by humans. One of the examples is that stars are not visible during the day (Fairchild, 2005). Also, the fact that the physical magnitude of the color attribute and the magnitude of human perception for the color attribute are not perfectly proportional could be one of the reasons. Therefore, the color appearance model developed in consideration of the characteristics of the surrounding environment and the state of adaptation of the observer is important in identifying how a human perceives color. Color appearance models are not only used to understand cognitive properties of color in the color science field, but also used in image enhancement, color matching among multiple devices, color matching between real scene and camera shot scenes, and various industrial fields such as painting, art, lamp, etc.

Color appearances of the objects are changing, depending on light sources. In everyday life, it is common to see a scene having two or more light sources together, or to look at an object that is shadowed by other objects. However, these situations might not be interpreted by current color appearance models, which are based on a single light source. With increasing interest in color reproduction of high dynamic scenes, color appearance research that can explain these multi illumination situations is necessary.

Conventional color appearance models (Fairchild, 1994, 1998; Fairchild & Berns, 1993; Luo, Lo, & Kuo, 1996; Luo & Morovic, 1996; Hunt, 1982, 1985, 1987, 1989, 1991, 1994) have been developed in a limited experimental condition. The color appearance models were developed primarily through psychophysical experiments based on data from an observer evaluating the presented color patch, which originated from a white patch under a uniform adaptation environment, otherwise known as a single lighting source. Current color appearance models are based on this simple adaptation environment. In real life, various lighting configurations can exist, and the observer's state of adaptation in these complex lighting environments is mostly unknown and difficult to define. Thus, current color appearance models may not be able to reflect the complex lighting condition in real life.
In this research, it is intended to explain color appearance phenomena in the context where observers alternately see two light sources having largely different illuminance levels being present at the same time. This study also attempts to identify the observer's state of adaptation in the presence of multiple lightings, by exploring how color appearance in terms of hue, brightness and colorfulness changes in

complex multiple lighting conditions, as opposed to single lighting conditions. From this point, two hypotheses have been developed.

Hypothesis 1*: Brightness perception and colorfulness perception will change in multiple lighting conditions as compared to those in single lighting conditions.*

Hypothesis 2*: Observers will adapt 1) to the lighting of the highest illuminance (global adaptation), 2) to the lighting where the color is directly placed (local adaptation), or 3) to the illuminance somewhere in between the two lightings (mixed adaptation).*

1.2 Research Outline

The research objective is to investigate color appearance change and identify the observer's state of adaptation under multiple lighting conditions. To build multiple lighting experimental settings, two lightings — one having high illuminance (7005 lux, 1680 cd/m^2) and the other having low illuminance (376 lux, 93 cd/m^2) — were prepared. The research scope is within photopic vision, whose range is from 10 to 10^8 cd/m^2. The high illuminance lighting used in this study has a value of 7005 lux, close to the full outdoor daylight in everyday life, and the low illuminance lighting has a value of 376 lux, similar to that of indoor office lighting (Engineering ToolBox, 2004).

The psychophysical experiment will be conducted to estimate color appearance and will be composed of 4 sessions according to 1) illuminance of lighting either high or low, and 2) observer's adaptation to the lighting conditions for either single lighting or multiple lightings.

Throughout the sessions, observers will evaluate the color appearance of 50 color patches via the magnitude estimation method in terms of hue, colorfulness and brightness. Observers will only be adapted to the low illuminance lighting in session 1 and evaluate color patches under low illuminance lighting. In session 2, observers will evaluate color patches under high illuminance lighting, adapting to the high illuminance lighting. In session 3 and 4, observers will be advised to alternate seeing the two lightings in turns, to inhibit becoming adapted to either specific lighting. Observers will estimate color patches placed under low illuminance lighting in session 3, and those placed under high illuminance lighting in session 4.

Through the color appearance estimation experiment under the presence of multiple lightings, the color appearance phenomenon will be analyzed in that context and will be compared. Then, the CIECAM02 color appearance model performance will be evaluated by comparing its color appearance prediction data with the color perception data obtained from this study both under single lighting and multiple lightings.

2

Literature Review

Chapter 2 Overview

In chapter 2, background knowledge for understanding the study of color appearance under multiple lightings will be described. Color appearance terminologies suggested by the CIE (Commission Internationale de l'Eclairage, a.k.a. International Commission on Illumination) and lighting terminologies defined by Standard Terminology of Appearance will be introduced. 'Adaptation' to lighting which can affect color appearance will also be described. Several phenomena that affect human color perception will be explained. The method of how to numerically represent colors as coordinates in color spaces and the color appearance model that can predict human color perception will also be illustrated.

2.1 Color and Lighting Terminologies

In this section, the CIE definition of color appearance terminologies will be introduced. The terminologies were extracted from the International Lighting Vocabulary (CIE,1987) produced by the CIE. Also, terminologies that can describe lighting conditions will be described and the terms were extracted from ASTM (Standard Terminology of Appearance)-E284-04 (ASTM International, 2004).

(Perceived) Color (CIE 17-198)

Color is the characteristic of visual perception that can be described by attributes of hue, brightness (or lightness) and colorfulness (or saturation or chroma).

(Psychophysical) Color (CIE 17-190)

Color is a specification of a color stimulus in terms of operationally defined values, such as 3 tristimulus values

Color Appearance (CIE 17-199)

Color appearance is an aspect of visual perception by which things are recognized by their color. In psychophysical studies, *color appearance* is the visual perception in which the spectral aspects of a visual stimulus are integrated with its illuminating and viewing environment.

Color Appearance Model (CIE 17-200)

Color appearance model is a model describing color appearance, built from descriptors of color stimuli

Hue (CIE 17-542)

Hue is an attribute of a visual perception according to which an area appears to be similar to one of the colors: red, yellow, green, and blue, or to a combination of adjacent pairs of these colors considered in a closed ring.

Chromatic Color (CIE 17-141)

In the perceptual sense, *chromatic color* is the perceived color possessing hue.

Achromatic Color (CIE 17-11)

In the perceptual sense, *achromatic color* is the perceived color devoid of hue.

Brightness (CIE 17-111)

Brightness is an attribute of a visual perception according to which an area appears to emit, or reflect, more or less light.

Lightness (CIE 17-680)

Lightness is the brightness of an area judged relative to the brightness of a similarly illuminated area that appears to be white or highly transmitting.

Colorfulness (CIE 17-233)

Colorfulness is an attribute of a visual perception according to which the perceived colour of an area appears to be more or less chromatic.

Chroma (CIE 17-139)

Chroma is the colorfulness of an area judged as a proportion of the brightness of a similarly illuminated area that appears white or highly transmitting.

Saturation (CIE 17-1136)

Saturation is the colorfulness of an area judged in proportion to its brightness.

Correlated Color Temperature (CIE 17-258)

Correlated color temperature is the concept of illustrating the color of illumination. By definition, *correlated color temperature* is the temperature of the Planckian radiator having the chromaticity nearest the chromaticity associated with the given spectral distribution on a diagram where the (CIE 1931 standard observer based) $u', \frac{2}{3}v'$ coordinates of the Planckian locus and the test stimulus are depicted (Unit: K).

Illuminance (ASTM E 284)

Illuminance is the luminous flux incident per unit of area.

Luminance (ASTM E 284)

Luminance is the luminous flux in a beam, emanating from a surface, or falling on a surface, in a given direction, per unit solid angle.

2.2 Adaptation

The adaptation is the process by which the state of the visual system is modified by previous and present exposure to stimuli that may have various luminance values, spectral distributions and angular subtenses (CIE,1987). The photoreceptors called rods and cones in the retina of the eye are the most responsible for the adaptation in the human visual system. The rods are exclusively in charge of adaptation at lower luminance levels, less than 1 cd/m^2, while cones exclusively function for higher luminance levels, more than 10 cd/m^2. Rods and cones both function for the intermediate luminance levels. The vision of which only rods take the charge is called scotopic vision while that of which cones exclusively function is referred to photopic vision. The vision where both rods and cones work is called mesopic vision. The transition from the rods to the cones makes the human visual system effectively adapt to the wide range of luminance levels (Fairchild, 2005).

The types of adaptation of interest in the color appearance field are dynamic adaptation and chromatic adaptation. Dynamic adaptation can be largely divided into two categories. The first is a dark adaptation. In the case of dark adaptation, it happens when the observer is in a bright place and then moves to a dark place. In other words, it means that the human eye is adapted to the bright lighting condition and then to the dark lighting condition. The pupil size of the human eye becomes larger to efficiently accept the photons, and the photoreceptors become more sensitive so that observers gradually discern objects even under a low luminance environment. The second is a light adaptation which is an inverse process of dark adaptation. Light adaptation occurs when observers move from a brighter place to a darker place. In this case, the pupil size of the eye becomes smaller so as to reduce the number of photons coming through the retina, and photoreceptors become less sensitive.

Chromatic adaptation is a visual process whereby approximate compensation is made for changes in the colors of stimuli, especially in the case of changes in illuminants (CIE, 1987). Chromatic adaptation can be exemplified with a classic phenomenon. When a white paper is shown under either daylight, LED light, tungsten lamp or fluorescent light, observers perceive the paper as being white although the spectral compositions of the illuminations are quite different.

2.3 Color Appearance Phenomena

Even though the colors having the same physical characteristics, the colors can appear not to be the same when they are viewed with different surrounds, backgrounds, sizes, shapes, illumination geometry, illumination level, illumination color, viewing conditions, etc. In this chapter, some of these color appearance phenomena will be described in the following sections, referenced in the book titled 'Color Appearance Models 2nd Edition' (Fairchild, 2013).

2.3.1 Simultaneous Contrast

In Figure 2.1, the gray square inside the black background looks brighter than that inside the white background. However, two gray squares are of the same luminance. This shows that the stimulus color may look different depending on the background, illustrating simultaneous contrast. This shows a greater effect when the two are complementary colors. Just as a dark background leads to a brighter appearance, and a light background leads to a darker appearance, red induces green and yellow induces blue.

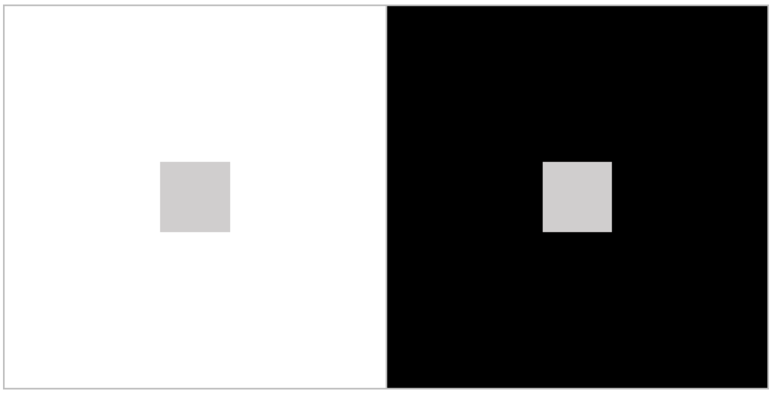


Figure 2.1 Example of Simultaneous Contrast

2.3.2 Helmholtz-Kohlrausch Effect

Helmholtz-Kohlrausch Effect explains brightness depends on luminance and chromaticity. In Figure 2.2, the red color and the magenta color looks brighter than the other colors. However, each of the five colors has the same luminance level change. This phenomenon happens because, as the saturation increased, the brightness of the color also became stronger.

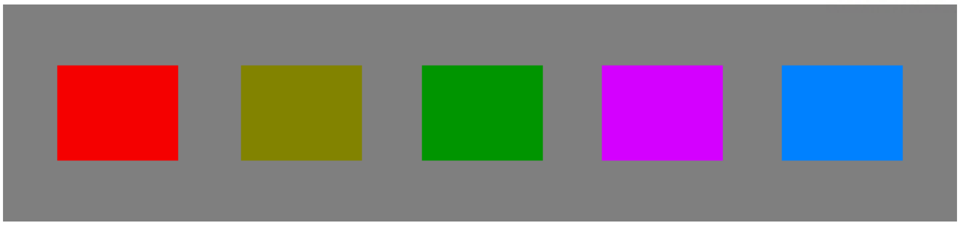


Figure 2.2 Example of Helmholtz-Kohlrausch Effect

2.3.3 Hunt Effect

The Hunt effect illustrates colorfulness increases with luminance. The color appearance of the object will change when the luminance level of illumination changes. As seen in Figure 2.3, the front sides of the color blocks where illumination falls more appears to be more colorful than the top sides of the color blocks where illumination falls less.

Figure 2.3 Example of Hunt Effect (Fairchild, 2005)

2.3.4 Discounting the Illuminant

Discounting the illuminant is the observer's cognitive ability to perceive color as its original color despite the color and level of illumination. This occurs under most typical viewing conditions as if the observer fully adapts to the illumination in the scene. Thus, observers perceive a white object as white under tungsten light. This phenomenon is also referred to 'color constancy'. Retinex theory suggested by Land in 1977 illustrates this phenomenon could be observed since a human would perceive color regarding the relative difference from the surrounding colors. Retinex theory will be described in section 2.7.

2.4 CIE XYZ Tri-stimulus Values

The CIE 1931 XYZ color space is the first color space defined mathematically based on the study of human color perception. Three elements are required to define a color. Light, the human visual system, and objects of interest are the elements. The CIE XYZ coordinates are calculated by integrating the spectrum of these three elements. Specifically, the spectral power distribution of the illuminant I(λ); the average human's chromatic response within 2° visual angle $\bar{x}(\lambda), \bar{y}(\lambda), \bar{z}(\lambda)$; and spectral reflectance (or transmittance) S(λ) of the object are needed. The CIE XYZ tri-stimulus values can be calculated using the following equations.

$$X = k \int S(\lambda) I(\lambda) \bar{x}(\lambda) d\lambda$$

$$Y = k \int S(\lambda) I(\lambda) \bar{y}(\lambda) d\lambda$$

$$Z = k \int S(\lambda) I(\lambda) \bar{z}(\lambda) d\lambda$$

where k is a constant and $\lambda \in [380,780]$

In the CIE XYZ color space, Y indicates luminance of a color, while X and Z are not assigned to denote specific color attributes. Thus, it was designed to express the chromaticities of the color by simply calculating the normalized values of XYZ. The chromaticities can be denoted by x and y calculated using the following equations.

$$x = \frac{X}{X+Y+Z}$$

$$y = \frac{Y}{X+Y+Z}$$

$$z = \frac{Z}{X+Y+Z}$$

2.5 CIE LAB Color Space

CIELAB is a uniform color space suggested by the CIE in 1976. CIELAB also can define color in terms of L* for the lightness, a* and b* for the color channels, red-green and yellow-blue. L * = 0 indicates black, and L * = 100 indicates white. If a * is negative, it is biased towards green, and if it is positive, it is biased towards. Blue if b * is negative and yellow if b * is positive. Since CIELAB is a uniform color space, the numerical difference of the CIELAB parameters means the equal amount of difference perceived by humans. The equations for calculating L*, a* and b* are following. In the equations, X_n, Y_n and Z_n are the CIE XYZ values of the reference white.

$$L^* = 116 * f\left(\frac{Y}{Y_n}\right) - 16$$

$$a^* = 500 * \left(f\left(\frac{X}{X_n}\right) - f\left(\frac{Y}{Y_n}\right)\right)$$

$$b^* = 200 * \left(f\left(\frac{Y}{Y_n}\right) - f\left(\frac{Z}{Z_n}\right)\right)$$

where

$$f(t) = \begin{cases} \sqrt[3]{t} & if\ t > (\frac{6}{29})^3 \\ \frac{t}{3 * (\frac{6}{29})^2} + \frac{4}{29} & otherwise \end{cases}$$

2.6 CIECAM02 Model

The color appearance model is a mathematical model that can predict the human color perception of a visual stimulus integrated with its illuminating and viewing environment. CIECAM02 is an advanced color appearance model developed in 2002 by the CIE TC 8-01 (Moroney et al., 2002). Input data for the CIECAM02 calculation are following: the relative tristimulus values of the stimulus (X, Y, Z) and the reference white (X_w, Y_w, Z_w); the absolute adapting luminance (L_A); the relative luminance of background (Y_b); the viewing condition parameters (c, N_c, F); and the degree of adaptation (D). There will be six outputs in terms of hue (H or h), lightness (J), brightness (Q), Chroma (C), colorfulness (M), and saturation (s). The detailed calculation procedure is as follows.

2.6.1 Viewing Condition Parameters

There are three viewing conditions determined in the CIECAM02 model: average, dim and dark. Viewing parameters, c the impact of the surrounding; N_c the chromatic induction factor; and F the factor determining the degree of adaptation should be determined according to the viewing conditions as shown in Table 2.1. In CIECAM02, intermediate values for these parameters can be used.

Table 2.1 Viewing Condition Parameters

Viewing Condition	c	N_c	F
Average Surround	0.69	1.0	1.0
Dim Surround	0.59	0.9	0.69
Dark Surround	0.525	0.8	0.8

2.6.2 Conversion from CIEXYZ to RGB Responses

The relative tristimulus values of the stimulus should be converted into RGB responses, using optimized transform matrix M_{CAT02}.

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = M_{CAT02} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix}$$

$$\text{where } M_{CAT02} = \begin{bmatrix} 0.7328 & 0.4296 & -0.1624 \\ -0.7036 & 1.6975 & 0.0061 \\ 0.0030 & 0.0136 & 0.9834 \end{bmatrix}$$

2.6.3 Degree of Adaptation

The factor D, the degree of adaptation, which is also called discounting D, will be determined based on surround F denoted in section 2.6.1 and the absolute adapting luminance L_A in cd/m^2. When L_A is unknown, it is usually calculated as 20% of L_W (the absolute luminance of the reference white) in cd/m^2. D = 0 means no adaptation occurred to the illuminant, and D = 1 indicates complete adaptation to the illuminant. Normally, L_A ranges from 0.65 to 1.0.

$$D = F\left[1 - \left(\frac{1}{3.6}\right)e^{-\frac{L_A+42}{92}}\right]$$

2.6.4 Conversion from RGB Responses to Adapted RGB Responses

Taking advantage of the factor D, adapted RGB responses should be converted from RGB responses.

$$R_C = \left[\left(\frac{Y_W D}{R_W}\right) + (1 - D)\right] R$$

$$G_C = \left[\left(\frac{Y_W D}{G_W}\right) + (1 - D)\right] G$$

$$B_C = \left[\left(\frac{Y_W D}{B_W}\right) + (1 - D)\right] B$$

2.6.5 Luminance-level Adaptation Factor

Luminance-level adaptation factor F_L is a function of the absolute adapting luminance L_A.

$$F_L = 0.2k^4(5L_A) + 0.1(1 - k^4)^2(5L_A)^{\frac{1}{3}}$$

where $k = 1/(5L_A + 1)$

2.6.6 Induction Factors

The factor for the brightness induction of the background N_{bb} and the chromatic background induction factor N_{cb} should be calculated, considering the background luminance effect on brightness and colorfulness of colors.

$$N_{bb} = N_{cb} = 0.725\left(\frac{1}{n}\right)^{0.2}$$

$$\text{where } n = Y_b/Y_w$$

2.6.7 Post-adaptation Nonlinear Compression

In order to express adapted RGB responses in more sophisticated cone responses, adapted RGB responses should be first converted to XYZ and then to Hunt-Pointer-Estevez space.

$$\begin{bmatrix} R' \\ G' \\ B' \end{bmatrix} = M_{HPE} M_{CAT02}^{-1} \begin{bmatrix} R_C \\ G_C \\ B_C \end{bmatrix}$$

$$\text{where } M_{HPE} = \begin{bmatrix} 0.38971 & 0.68898 & -0.07868 \\ -0.22981 & 1.18340 & 0.04641 \\ 0.00000 & 0.00000 & 1.00000 \end{bmatrix}$$

$$\text{, and } M_{CAT02}^{-1} = \begin{bmatrix} 1.096124 & -0.278869 & 0.182745 \\ 0.454369 & 0.473533 & 0.072098 \\ -0.009628 & -0.005698 & 1.015326 \end{bmatrix}$$

For the application of a nonlinear response compression, the post-adaptation cone responses are then calculated using the following equations.

$$R'_a = \frac{400\left(\frac{F_L R'}{100}\right)^{0.42}}{27.13+\left(\frac{F_L R'}{100}\right)^{0.42}} + 0.1 \quad , \quad G'_a = \frac{400\left(\frac{F_L G'}{100}\right)^{0.42}}{27.13+\left(\frac{F_L G'}{100}\right)^{0.42}} + 0.1 \quad , \quad B'_a = \frac{400\left(\frac{F_L B'}{100}\right)^{0.42}}{27.13+\left(\frac{F_L B'}{100}\right)^{0.42}} + 0.1$$

2.6.8 Opponent Color Dimensions

Initial opponent color dimensions a and b are determined using the following equations. a denotes the red-green dimension while b denotes the yellow-blue dimension.

$$a = R'_a - \frac{12G'_a}{11} + B'_a/11$$

$$b = \frac{1}{9}(R'_a + G'_a - 2B'_a)$$

2.6.9 Hue

h denotes hue angle, expressed from 0° to 360° when H indicates hue quadrature, ranging from 0 to 400. The factor e is an eccentricity factor.

$$h = tan^{-1}\left(\frac{b}{a}\right)$$

$$H = H_i + \frac{\frac{100(h - h_i)}{e_i}}{\left(\frac{h - h_i}{e_i}\right) + \frac{(h_{i+1} - h)}{e_{i+1}}}$$

where $e_t = 1/4\left[cos\left(\frac{h\pi}{180} + 2\right) + 3.8\right]$

Table 2.2 Conversion from Hue Angle to Hue Quadrature

	Red	Yellow	Green	Blue	Red
i	1	2	3	4	5
h_i	20.14	90.00	164.25	237.53	380.14
e_i	0.8	0.7	1.0	1.2	0.8
H_i	0	100	200	300	400

2.6.10 Achromatic Response

The achromatic response using the weighted summation of nonlinear adapted cone responses adjusted with the brightness induction factor is calculated prior to computing lightness and brightness.

$$A = \left[2R'_a + G'_a + \left(\frac{1}{20}\right)B'_a - 0.305\right]N_{bb}$$

2.6.11 Lightness

Lightness is calculated using achromatic response. A_w indicates an achromatic response for the reference white.

$$J = 100\left(\frac{A}{A_W}\right)^{cz}$$

$$\text{where } z = 1.48 + \sqrt{n}, \quad (n = Y_b/Y_w)$$

2.6.12 Brightness

Brightness is computed using surround factor c; lightness J; achromatic response for the reference white A_w; and the luminance-level adaptation factor F_L.

$$Q = \left(\frac{4}{c}\right)\sqrt{\frac{J}{100}}(A_W + 4)F_L^{0.25}$$

2.6.13 Chroma

Chroma is calculated using a temporary quantity t; lightness J; and the ratio of background luminance to the luminance of the reference white n. t is determined by chromatic adaptation factors for surround (N_c) and background (N_{cb}); the eccentricity factor e_t; opponent color dimension factors a and b; and weighted summation of nonlinear adapted cone responses.

$$C = t^{0.9}\sqrt{\frac{J}{100}}(1.64 - 0.29^{n})^{0.73}$$

$$\text{where } \ t = \frac{\left(\frac{50000}{13}\right)N_c N_{cb} e_t \sqrt{a^2+b^2}}{R'_a + G'_a + \left(\frac{21}{20}\right)B'_a}$$

2.6.14 Colorfulness

Colorfulness is calculated using chroma C and the luminance-level adaptation factor F_L. It can be seen that the colorfulness is affected by luminance level.

$$M = CF_L^{0.25}$$

2.6.15 Saturation

Saturation is determined by colorfulness M and brightness Q.

$$s = 100\sqrt{\frac{M}{Q}}$$

2.7 Retinex Theory

Retinex theory (Land, 1977) was suggested by Land in 1977. Retinex is a compound word of 'retina' and 'cortex', and the theory claims that color perception is achieved by the collaborative mechanism of the eye and the brain. According to the theory, observers do not perceive the color as it naturally appears under the change of lighting. Observers can recognize the original color of the object by excluding the illumination effect through the relationship between the color of interest and its surrounding colors. In addition, it was found that the lightness of color under one lighting can be perceived as the same signal under another lighting. When different lights are projected onto the same scene, the lightness of the white under each lighting is different. However, observer relatively evaluates the lightness of the surrounding colors based on the lightness of the white under each lighting (local adaptation), the same component can be perceived as having the same lightness signal, even if placed under different lighting. Retinex theory algorithm is widely used in the image processing field.

2.8 iCAM06

The iCAM stands for the image color appearance model. The iCAM is widely used in the image processing field. The iCAM06 (Fairchild and Johnson, 2002) was initially suggested by Fairchild and Johnson in 2002. The model explains local adaptation for high dynamic range scenes. In the iCAM model, the color appearance of each component is derived by setting different white for each location using surrounding background information. It is noticeable that this model considers local adaptation, as opposed to the CIECAM02 model described in 2.6, which applies only one reference white for the whole scene.

3

Experiment

Chapter 3 Overview

In Chapter 3, the overall experimental design for the study of color appearance under multiple lightings will be described. Experimental settings including the characteristics and specification of lightings used for the research and color patches used as experimental stimuli will be explained. The configuration of the experiment will be illustrated in detail session by session. The psychophysical experimental method used in the research and observer color appearance evaluation training process will be introduced. Experimental procedures will be explained in time order.

3.1 Experiment Outline

In this research, the color appearance of 50 color patches collected from the NCS (Natural Color System) album (Scandinavian Color Institute AB, Stockholm, Sweden, 2004-2007) was estimated, when there were two lightings having largely different illuminance levels (7005 lux and 375 lux) at the same time. Higher illuminance is 19 times higher than the lower illuminance. The experiment consists of four sessions according to the illuminance level of the lighting where the test color patches will be directly shown either under high illuminance or under low illuminance and the observer's adaptation to the lighting conditions (for either single lighting or multiple lightings). A total of 7 observers participated in the experiment and they evaluated color appearance in terms of hue, colorfulness and brightness, based on the magnitude estimation technique. Color perception results will be compared in between the sessions. Also, the performance of the color appearance model CIECAM02 will be identified.

3.2 Measurement Devices

3.2.1 Spectrophotometer (SP64, X-Rite)

A spectrophotometer is usually used for measuring reflectance or transmittance properties of a material as a function of wavelength. Spectrophotometer, SP64 (X-Rite) in Figure 3.1 was used to measure the color of interest. The geometry of the spectrophotometer is d/8° and integrating sphere diameter is 2.2”. Having geometry of d/8° means the device measures the reflected light from the object at an 8° angle. The spectral range is 400 – 700 nm and the measuring interval is 10 nm. As an output, relative CIE XYZ values, CIE LAB values, and other color properties can be collected.

Figure 3.1 Spectrophotometer (SP64, X-Rite)

3.2.2 Spectroradiometer (CS-2000, Minolta)

Spectroradiometer, CS-2000 (Konica Minolta) in Figure 3.2, is to measure the radiant power of the color of interest so that it can give the absolute CIE XYZ values as an output. There are three options for the measuring angle of the device, 1°, 0.2° and 0.1°. The device measures radiant power in 1 nm steps from 380nm to 780 nm under 2° observer condition. Having a 2° observer condition means it is following the CIE color matching function that represents the average human’s chromatic response within a 2° visual angle.

Figure 3.2 Spectroradiometer (CS-2000, Minolta)

3.2.3 Chromameter (CL-200, Minolta)

Chromameter, CL-200 (Konica Minolta) in Figure 3.3, is able to measure the color temperature, illuminance, chromaticity, excitation purity, and dominant wavelength of various light sources.

Figure 3.3 Chromometer (CL-200, Minolta)

3.3 Experimental Settings

The overall experimental setting is described in Figure 3.4. In order to make high dynamic multi illumination scenes, two light sources were prepared. High illuminance light was from 5-channel LED booth and low illuminance light was from office lighting. The specification of the lightings was measured by chromameter (CL-200, Minolta) each time right before the experiment. Correlated color temperature (CCT) of the lighting booth was controlled to be as similar as possible with that of office lighting whose CCT was fixed. The test color patch and the reference color patch to be used as a standard for evaluating the test color will be placed under one of the two lightings according to the experimental conditions which will be described in the following sections. The positions of the color patches were fixed where they didn't seem to be glare.

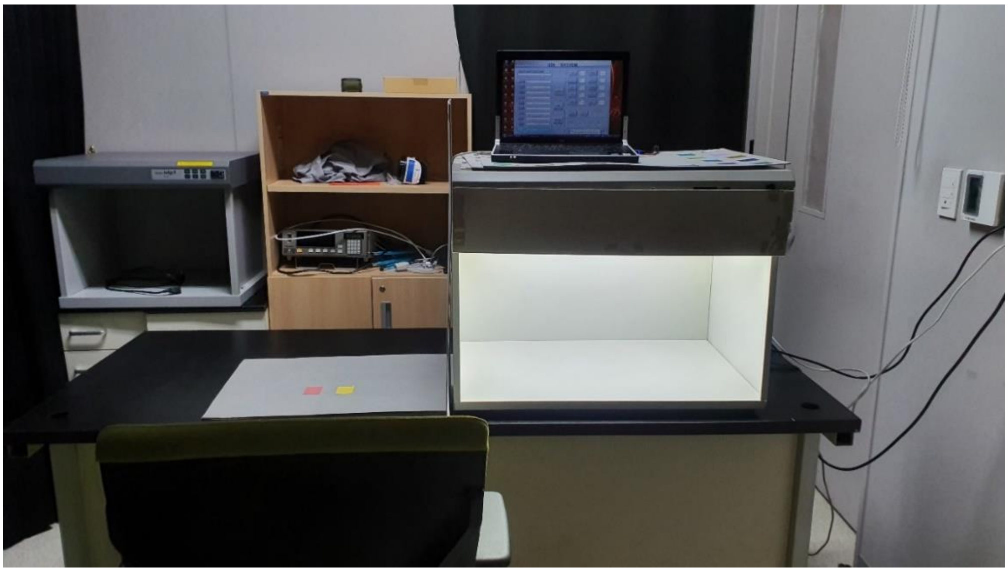


Figure 3.4 Experimental Settings

A five-channel LED booth was used to produce high illuminance lighting conditions. The LED booth was placed on an 80 cm-height desk. The LED channels consist of red, green, blue, warm white and cool white lightings. The size of the booth was 67 (width) * 48 (depth) * 51 (height) cm. The inner side of the booth was uniformly painted in mid-grey color, and its relative CIE XYZ values (X, Y, Z) = (32.8, 34.9, 36.6) were measured by a spectrophotometer (SP64, X-Rite) under D65 and 2° observer condition. The light from the LED channels was evenly projected on the bottom side of the lighting booth. Illuminance and correlated color temperature (CCT) were measured by chromameter (CL-200, Minolta) at the bottom center of the lighting booth prior to every experimental session to check the stability of the lighting. The average illuminance of the lighting booth measured during all experimental sessions was about 7004.6 (±325.8) lux. The correlated color temperature of high illuminance lighting was about 5538.1 (±76.3) K. The maximum luminance was acquired from the white patch measurement by the spectroradiometer (CS-2000, Minolta) under the lighting as 1680 cd/m^2.

Office lighting was used to build a low illuminance lighting condition. Specification of the lighting was measured by the chromameter, CL-200, prior to each experimental session. The illuminance and CCT of the office lighting were measured on the desk where the lighting booth was installed, specifically on the left side of the lighting booth, in the middle of the location where the reference patch and test patch were to be placed. The average illuminance was about 375.7 (±6.0) lux and CCT was about 5405.3 (±20.4) K. For color estimation under low illuminance lighting, color patches were placed on a mid-grey color plate on the left side of the lighting booth. The relative CIE XYZ values of the color plate measured by the spectrophotometer, SP64, were (X, Y, Z) = (29.59, 31.30, 30.70). The maximum luminance was acquired from the white patch measurement by the spectroradiometer (CS-2000, Minolta) under the lighting as 93 cd/m^2.

The spectral power distributions of the two lightings measured by the spectroradiometer (CS-2000, Minolta) are described in Figure 3.5. The spectrum was acquired from the white patch measurement under high illuminance lighting and low illuminance lighting, respectively. The spectra of both lightings were rescaled to have its maximum value as 1. The shapes of the two spectra are quite different. Different spectral shapes may be a factor that can affect color appearance. Therefore, in section 3.5.2, the appearance estimates of hue, brightness, and colorfulness, taking into account high illuminance lighting and low illuminance lighting effect, respectively, in the CIECAM02 color space, will be calculated to discuss whether different spectral shapes affected the color appearance.

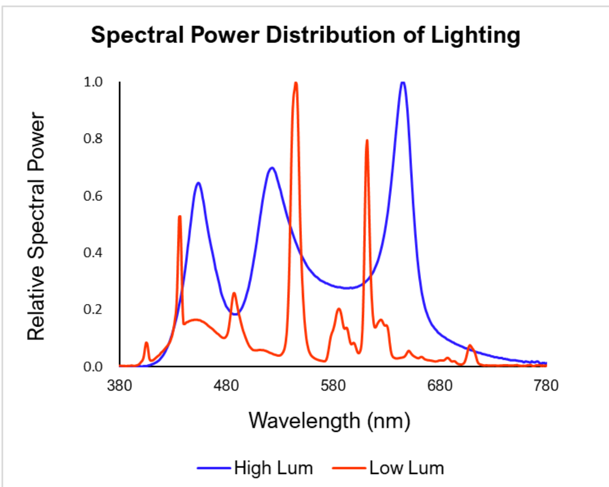


Figure 3.5 Spectral Power Distribution of Lightings

3.4 Experimental Configuration

There was a total of four sessions in this experiment having different illuminance of the lighting where the test color patches will be evaluated and different observer's adaptation to the lighting conditions. There were two options of the illuminance of lightings at which test color patches to be placed: under high illuminance lighting; and under low illuminance lighting. There were three types of the observer's adaptation to the lighting conditions: under low illuminance; under high illuminance; and under both low illuminance and high illuminance (mixed adaptation) conditions. The overall experimental composition is described in Table 3.1, and the detailed configuration of each session will be illustrated in the following subsections.

Table 3.1 Observer's Adaptation and Color Patch Position

	Adaptation	Ref. Patch	Test Patch
Session 1	Low Lum.	Low	Low
Session 2	High Lum.	High	High
Session 3	Mixed Adaptation	Low	Low
Session 4	Mixed Adaptation	Low	High

3.4.1 Session 1 – Patch under Low Lum. & Low Lum. Adaptation

In session 1, as depicted in Figure 3.6, both reference color patch and test color patch were placed under low illuminance lighting. It was intended that observers only adapt to low illuminance lighting. Thus, a partition was added in between the two lightings so as to block the light coming from the high illuminance lighting.

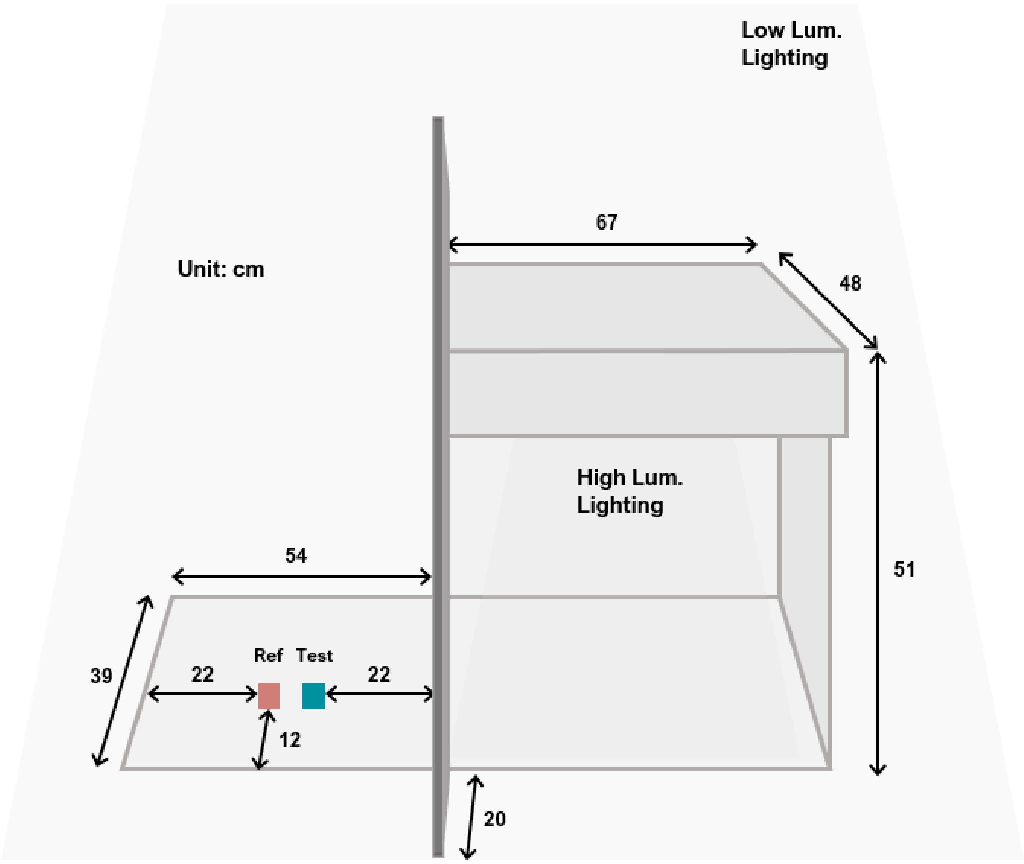


Figure 3.6 Session 1 Configuration (Patch under Low Lum. & Low Lum. Adapt.)

3.4.2 Session 2 – Patch under High Lum. & High Lum. Adaptation

In session 2, as depicted in Figure 3.7, both reference color patch and test color patch were placed under high illuminance lighting. The partition was added in between the two areas. The observer was advised to look into the lighting booth so as to only adapt to the high illuminance lighting.

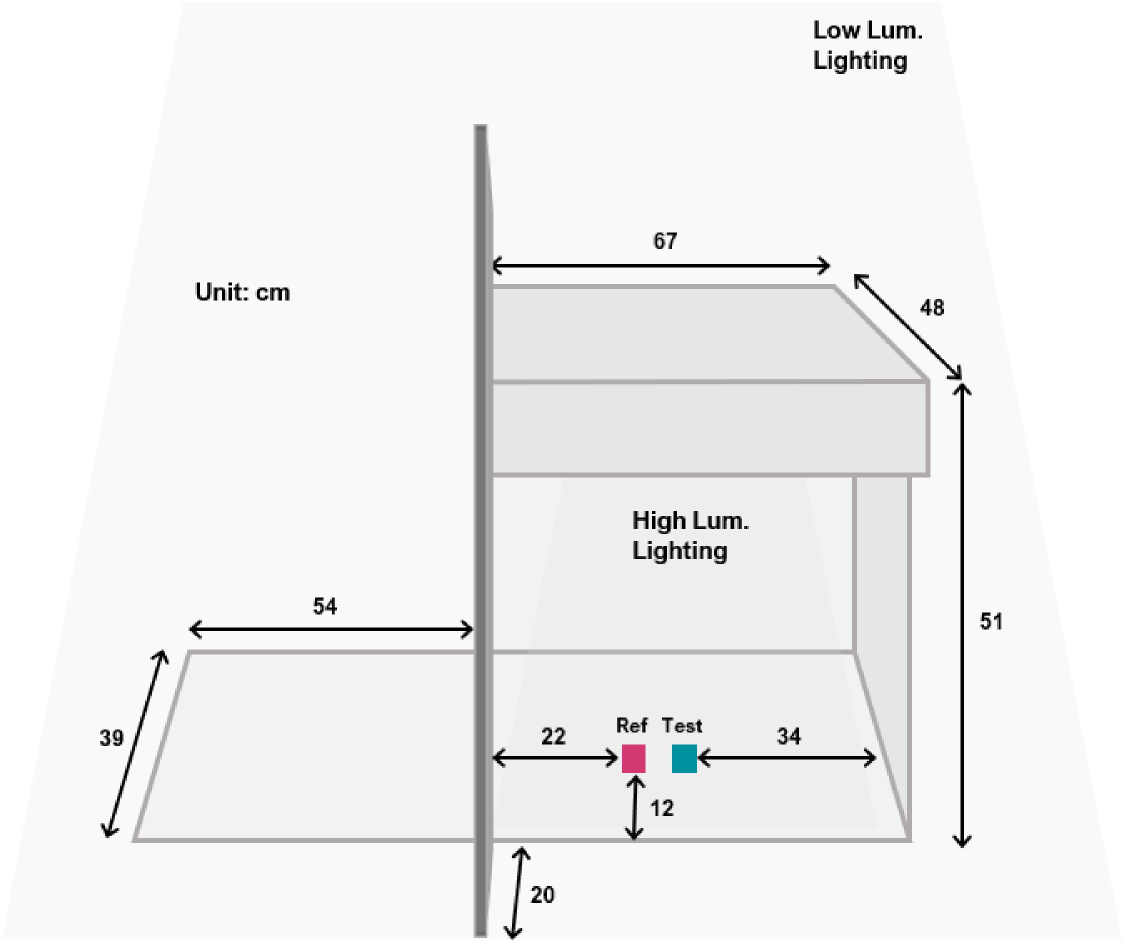


Figure 3.7 Session 2 Configuration (Patch under High Lum. & High Lum. Adapt.)

3.4.3 Session 3 – Patch under Low Lum. & Mixed Adaptation (High & Low Lum.)

Figure 3.8 shows the overall configuration of session 3. In this session, it was assumed that observers adapt to both lightings, alternately seeing two lightings. Observers ought to evaluate the color appearance of the test color patches placed under low illuminance lighting while the reference color patch was also placed under low illuminance lighting. Even though both reference and test color patches were placed under low illuminance lighting, observers were advised to alternate seeing the two lightings in turns, to inhibit becoming adapted to either specific lighting. For mixed adaptation, the partition installed in between the lightings was removed in this session.

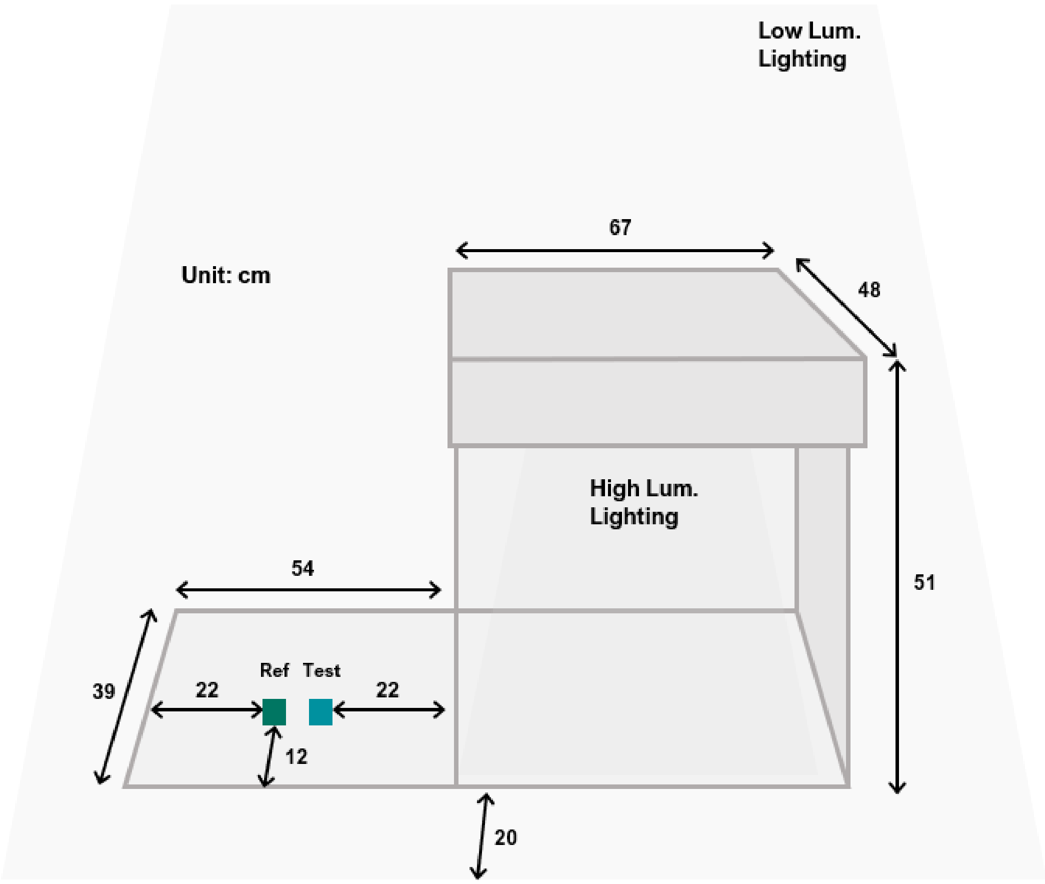


Figure 3.8 Session 3 Configuration (Patch under Low Lum. & Mixed Adapt.)

3.4.4 Session 4 – Patch under High Lum. & Mixed Adaptation (High & Low Lum.)

As in session 3, it was assumed that observers adapt to both lightings in session 4. Observers evaluated the color appearance of the test color patches, alternately seeing two lightings. As depicted in Figure 3.9, since the reference color patch was placed under low illuminance lighting when the test color patches were to be placed under high illuminance lighting, participants had no choice but to naturally look at both lightings alternately. For mixed adaptation conditions, partition was removed in this session as in session 3.

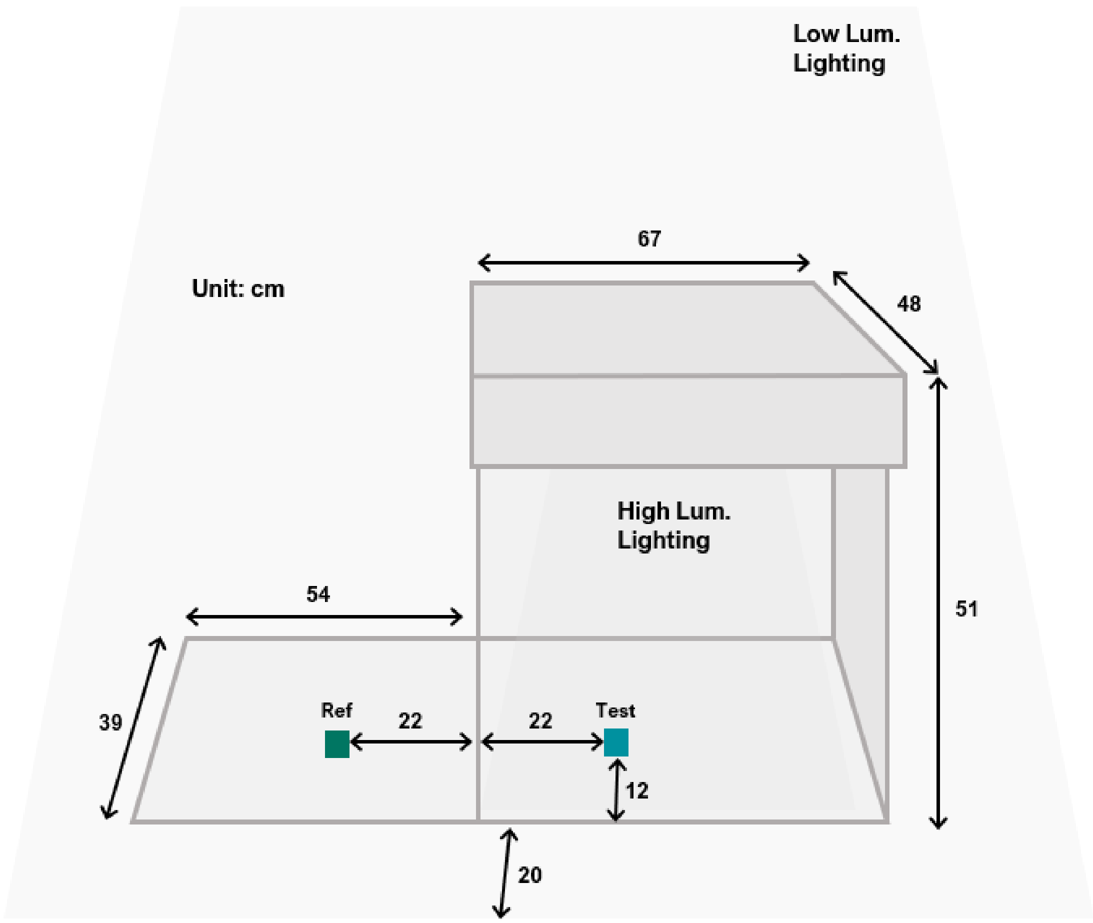


Figure 3.9 Session 4 Configuration (Patch under High Lum. & Mixed Adapt.)

3.5 Experimental Stimuli

All color patches used in this research were extracted from the NCS (Natural Color System) album (Scandinavian Color Institute AB, Stockholm, Sweden, 2004-2007). Firstly, a total of 53 color patches were extracted, and the selected color patches were evenly distributed across the hue, blackness, and chromaticness domains in Natural Color System. Among them, 3 patches were used as the reference patches. The reason for using different reference color patches according to the observer's adaptation to the lighting condition is as follows. If the same reference color patch would be used in all sessions, the observer might be biased that, the brightness and colorfulness of the reference color patch should be assigned differently under different adaptation lighting conditions. Therefore, the pure visual perception of the color stimulus could be biased, so different reference color patches were to be used according to the observer's adaptation to the lighting conditions. Additionally, as for the magnitude estimation technique, it was revealed in the previous studies that psychophysical scales with or without the experimenter-predefined reference were found to be almost identical even though a random reference was given to each observer (Stevens, 1975; Gescheider, 1997). Since using a different reference color patch for each session will have no impact on the color visual assessment, so it was finally decided to use different reference color patches for each adaptation to the lighting conditions.

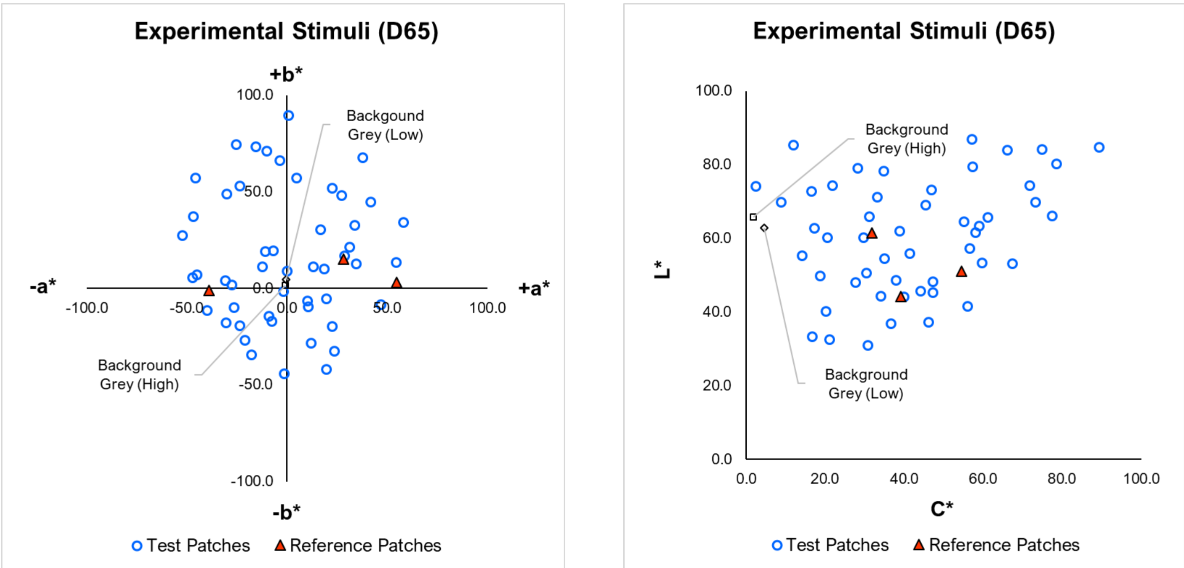
50 color patches out of 53 color patches except three reference color patches were used as test color patches. Randomly designated 5 color patches (S 1030-Y40R, S 1575-R10B, S 2555-B30G, S 3020-Y80R, S 3050-B20G) would be presented twice in the experiment to check each observer's repeatability (response consistency). Therefore, a total of 55 patches, including these 5 patches, would be presented in the experiment. The presented order of the test color patches was randomized for each participant and for each session.

Color patches were measured by two devices: 1) by spectrophotometer (SP64, X-Rite) to get relative tristimulus values under D65 and 2° observer condition, and 2) by spectroradiometer (CS-2000, Minolta) to get absolute tristimulus values under actual experimental conditions. Detailed measurement conditions and stimuli distribution in color spaces will be described in the following subsections.

3.5.1 Stimuli Distribution (Relative XYZ, D65 and 2° Observer)

The relative XYZ values and CIE LAB values were obtained based on D65 and 2° observer conditions, using the spectrophotometer (SP64, X-Rite). These values were measured to select the reference patches. The distribution of the color patches in a*-b* space and C*-L* space is described in Figure 3.10. Among 53 patches, the three color patches (S 2040-Y90R, S 1070-R20B, S 3555-B80G) that had similar L* or

C* values to the average L* or average C* values of all color patches were selected as the reference color patches for color attributes magnitude estimation. The CIE xy chromaticities of color patches are shown in Figure 3.11 with spectral locus. The spectral locus and the inner side of it represent all the colors that humans can perceive.



(a) a*-b* Space

(b) C*-L* Space

Figure 3.10 Experimental Stimuli Distribution (D65) in CIELAB Space

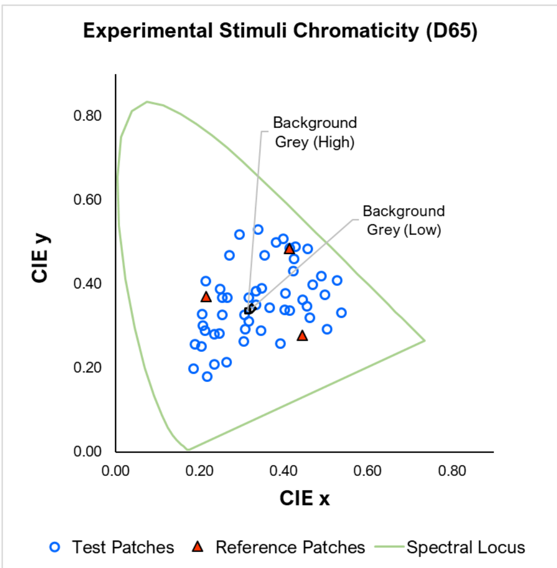


Figure 3.11 The CIE xy Chromaticity (D65) of Experimental Stimuli

3.5.2 Stimuli Distribution (Absolute XYZ, Actual Experimental Scene)

The absolute XYZ values were measured under actual experimental conditions, using the spectroradiometer (CS-2000, Minolta). The absolute XYZ values were measured to be used in the CIECAM02 calculation. The measured values can be found in Appendix 2. Color patches were measured both under high illuminance lighting and under low illuminance lighting, respectively. The measurement geometry is shown in Figure 3.12. CS-2000 was set, forming the CIE standard geometry 0°/45°, which means the device looks down the color patches at an angle of 45° as described in the figure. The measuring height of the spectroradiometer was the same with that of observer eye-height in actual experimental condition as 120 cm, considering that the color patch would be placed on an 80 cm-height desk or in the lighting booth installed on the same desk.

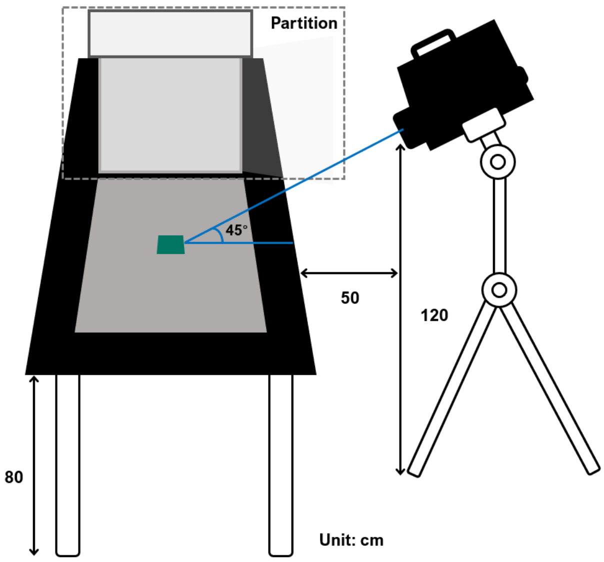
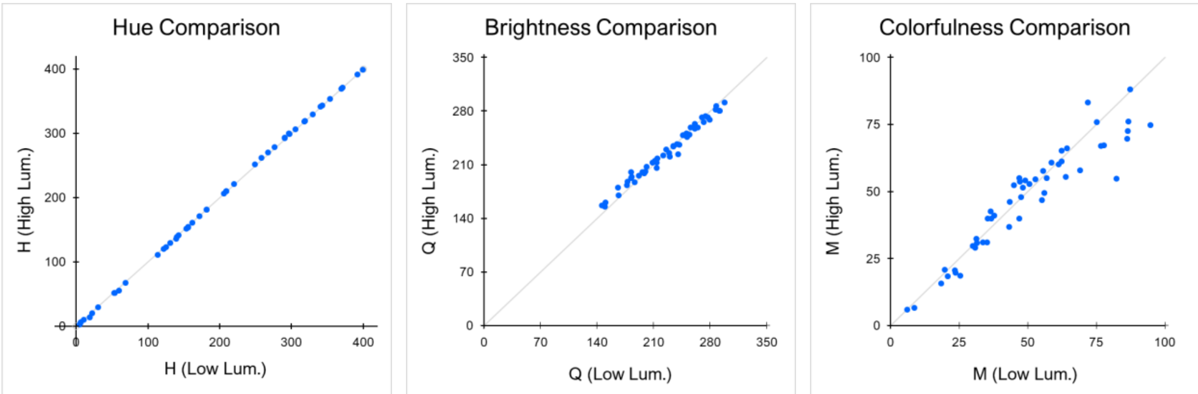


Figure 3.12 Color Patch Measurement Geometry (Spectroradiometer, CS-2000)

The measured XYZ values were converted into values in CIECAM02 space in terms of hue, brightness and colorfulness so as to see if there was color appearance change due to spectral shape difference between the two lightings as mentioned in section 3.3. Hue, brightness and colorfulness appearance under high illuminance and low illuminance in CIECAM02 space were calculated based on the white patch under each lighting and compared as shown in Figure 3.13. The CIE XYZ value of the white patch under high illuminance is (X, Y (cd/m^2), Z) = (1546.5, 1680.6, 1420.9) and that under low illuminance is (X, Y (cd/m^2), Z) = (85.96, 93.12, 82.38). To see only the difference in color appearance that comes from the spectral difference, all other input parameters were assigned the same values. As seen in Figure 3.13 (a) and (b), there was little hue shift and brightness change caused by the spectral difference of the two lightings. In (c), although random scatterings among data points were found, it was hard to find a systematic change in colorfulness appearance prediction data under two spectrally different lightings according to their illuminance levels. When the color difference under those two lightings was calculated in CIELAB space, the average DE*ab of all colors was 9.4. The two colors (S 0580-Y and S 2070-G50Y) having large chromaticness values in Natural Color System were found to have a large color difference, which was 25.8 and 30.1, respectively. Excluding these two colors, the average color difference was 8.7. Thus, it should be considered that the study was conducted in an environment having two spectrally different lightings, which had 19 times illuminance difference, making the color appear to be different about 9.4 in CIELAB space.



(a) Hue (b) Brightness (c) Colorfulness

Figure 3.13 Experimental Stimuli Distribution in CIECAM02 Space in Actual Scenes

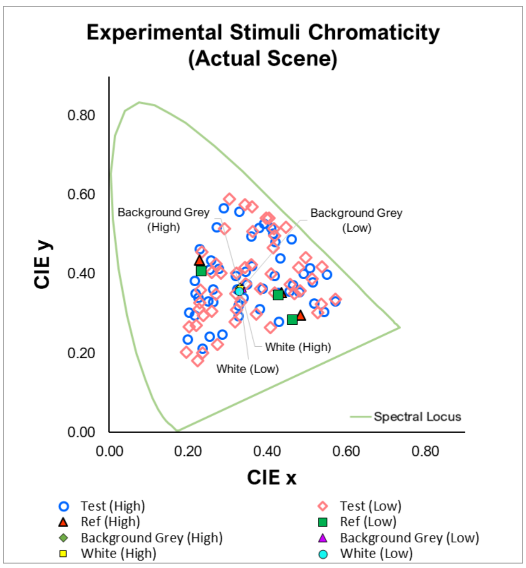


Figure 3.14 The CIE xy Chromaticity of Experimental Stimuli in Actual Scenes

3.5.3 Visualization of Stimuli

It was possible to visualize the reference color patches and test color patches extracted from the NCS album by using the NCS Navigator 2.0 (NCS Colour AB, 2011) provided via the NCS website. NCS Navigator is a tool giving the closest RGB, CMYK and Lab values to NCS 1950 original colors. Figure 3.15 shows the digital representation of reference color patches used in the research and Figure 3.16 shows that of test color patches. This digital representation of color patches may differ from the actual colors viewed from the physical color patches to some extent, so please regard them as a reference only and check with physical NCS color patches for accuracy.

Figure 3.15 Reference Color Patches (S 2040-Y90R, S 1070-R20B, S 3555-B80G)

Figure 3.16 Test Color Patches

3.6 Psychophysical Experimental Method – Magnitude Estimation

A magnitude estimation method was taken in this experiment. Magnitude estimation technique is one of the widely used psychophysical experimental methods. It is for observers to make a direct numerical estimation of the given stimulus in terms of attributes of interest based on their perception. In this technique, a reference stimulus is usually given with a fixed numerical value for perception basis so that observers can relatively assign a specific number to the given test stimulus based on their perception as compared to the number of the reference (Prins, 2010). In this research, observers evaluated the color appearance of the test color patches in terms of hue, brightness and colorfulness, taking advantage of the magnitude estimation technique. The CIE definitions of hue, colorfulness and brightness are described in section 2.1.

3.6.1 Hue Estimation

As for hue, observers should report hue of the test color either among red, yellow, green or blue, or report in a way of mixing two unique hues in percentage scale (e.g. red 50%, yellow 50% for an orangish color). In this case, red-green and yellow-blue cannot be mixed. If observers cannot find any color in the patch, they can answer the color is neutral. Visual hue estimation data will be converted into a hue quadrature scale (0-400 scale) afterward.

3.6.2 Brightness Estimation

For brightness estimation, there is a reference color patch having an anchored number for brightness perception, which will be placed side by side with the test color patch. Observers should assume that the brightness of the ideal black in their minds would be 0. Brightness estimation has no upper limit. In session 1, given the brightness of the reference color patch (S 2040-Y90R) under low luminance lighting is 50, observers should relatively assign a specific number to the brightness of test color patches under low luminance lighting. In session 2, observers will assign a number to the brightness of a new reference color patch (S 1070-R20B) under high luminance lighting, given the brightness of the reference color patch used in session 1 is 50, based on their memory. Based on the newly set brightness of the new reference color patch, observers will evaluate the brightness of the test color patches. Similarly, observers should assign a number to the brightness of the new reference color patch (S 3555-B80G) under low luminance lighting in session 3, compared to that of reference color patch in session 1. Lastly, session 4 shares the same reference color patch (S 3555-B80G) and its pre-assigned brightness in session 3 since the observer's adaptation environment is the same for the two sessions. Considering the pre-assigned brightness of the reference color patch, observers will estimate the brightness of test color patches.

3.6.3 Colorfulness Estimation

In colorfulness estimation, the same reference patch used in brightness estimation will also be used as a reference patch. The reference color patch has a fixed number for a colorfulness perception basis. For a neutral color, the colorfulness of the color patch would be 0. Colorfulness estimation has no upper limit. In session 1, the colorfulness of a reference patch (S 2040-Y90R) will be given as 50. Colorfulness setting logics for the reference color patches and the way evaluating colorfulness of test color patches in other sessions are the same as those for brightness estimation described in section 3.6.2.

3.7 Experimental Participants

One male and six females, a total of seven observers, took part in the experiment. This study is based on a psychophysical evaluation method called magnitude estimation. For these studies, it is far more important to acquire reliable participants who are skillfully trained in color appearance assessment than the number of participants. Therefore, in this study, only seven people selected through long training sessions participated in the experiment. In the previous color appearance study, only six skillfully-trained participants have extracted enough data (Luo et al., 1991).

All observers were Korean and in their 20s. All observers had the normal color vision, who passed the Ishihara color blind test (Figure 3.17). If observers had a normal color vision, they could read the number written in the circle. Also, they had no trouble differentiating hue, passing Farnsworth–Munsell 100 hue test (Figure 3.18). Observers had time to arrange the color caps in order between the color caps that are fixed on both sides of each tray, and if they listed correctly, they would have no problem with hue perception.

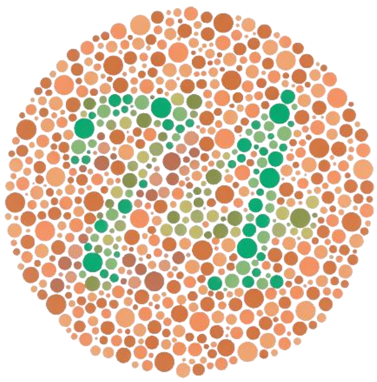


Figure 3.17 Ishihara Color Blind Test

Figure 3.18 Farnsworth-Munsell 100 Hue Test

After validating observers having a normal color vision, observers had time to understand the concept of color appearance attributes, specifically hue, brightness and colorfulness, using The new Munsell student color set (Long, 1996) in Figure 3.19. Observers had time to arrange Munsell color chips on the student workbook sheet along hue, value and chroma dimensions.

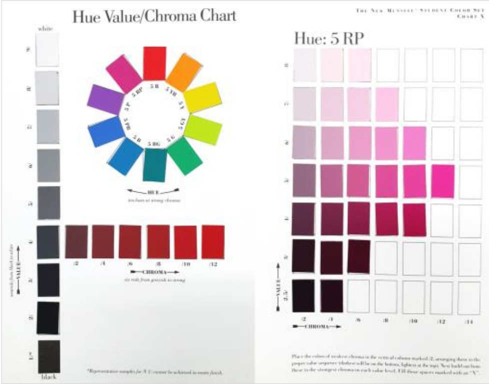


Figure 3.19 The New Munsell Student Color Set

Also, observers did pre-experiment, which had the same experimental qualities with the main experiment for observers to get used to the concept of color appearance and be familiarized with the psychological experiment (magnitude estimation) technique itself, but with fewer experimental stimuli (with 16 test color patches). Color patches used in the pre-experiment were randomly extracted from the NCS album and they were not included in the real experimental stimuli.

3.8 Psychophysical Experimental Procedure

The overall experimental process took 5 days for each observer. On the first day, observers got color training and pre-experimental sessions. From the second day, each experimental session, a total of four sessions, was conducted per day.

Session 1 ~ Session 4 proceeded sequentially, and the reasons for not randomizing the session order are as follows. First of all, session 1 and session 2 were experiments under single lighting, which had the most basic experimental setting. Therefore, it would be easier for observers to participate in an experiment having a simple lighting condition before they participate in a complex lighting configuration such as multiple lights. Thus, session 1 and session 2 proceeded prior to session 3 and session 4. There is also a need for setting the brightness and colorfulness of the reference color patches of other sessions based on the reference color patch given in session 1 so that session 1 proceeded the first of all. Session 3 and session 4 were for multiple lighting conditions. In session 3, the reference color patch and the test color patch were in the same lighting (low illuminance lighting), while in session 4 the reference color patch was in low illuminance lighting and the test color patch was in high illuminance lighting. Therefore, session 4, which was expected to be more difficult, was configured in the last order.

3.8.1 Introduction of Experiment and Observer Training

On the first day, an experimental instruction was given to the observers at the beginning of the experiment. As for the contents of the instruction, shown in Appendix 1, objective of the experiment, the CIE definition of hue, colorfulness and brightness as in section 2.1, how to evaluate each color attribute in psychophysical experimental method, experimental procedure, and blanks for observer personal information (name, sex and whether having color blindness or color weakness) were described. After observers being fully aware of the experiment, observers did the color test; got a color appearance training session; and participated in pre-experiment as described in section 3.7.

3.8.2 Session 1 (Low Lum, Low Adapt)

On the second day, observers participated in session 1. Observers were asked to sit on the chair 50 cm away from the 80 cm desk where the lighting booth was installed, forming a natural look-down posture. The sitting eye-height of the observers was about 120 cm. Observers adapted to the low illuminance lighting for two minutes, staring left side of the partition so as to only adapt to the lower illuminance lighting as seen in Figure 3.20. Both reference color patch and test color patch were placed under low illuminance lighting. Pinkish orange color, S 2040-Y90R, was used as a reference color patch in session 1. The brightness and colorfulness of the reference color patch were set to be 50 and 50, respectively. Observers evaluated 55 color patches, including repeated 5 patches for repeatability check, in terms of brightness and colorfulness based on the reference color patch, as well as hue. The color patch presentation order was randomized. One test color patch was placed where the test patch should be placed (next to the reference color patch in this session), and the observer reported the hue, brightness and colorfulness estimates of the test color patch, and the experimenter recorded the observer's response. Then, the existing test color patch was removed, and the next test color patch was presented. This process was repeated for a total of 55 color patches.

Figure 3.20 Session 1 Experimental Environment

3.8.3 Session 2 (High Lum, High Adapt)

On the third day, session 2 proceeded. Before the session began, observers went through the process of setting the brightness and colorfulness of the new reference color patch. Saturated pink color, S 1070-R20B, was used as a reference color patch in this session. The brightness and colorfulness of the new reference color patch ought to be set based on the previous reference color patch, S 2040-Y90R. Observers firstly adapted to the low illuminance lighting (left side of the partition) for two minutes, then they evaluated five random color patches (S 0580-Y90R, S 1075-G90Y, S 2555-B30G, S 3060-B90G, S 4020-G70Y) in terms of hue, brightness and colorfulness, given the brightness and colorfulness of the previous reference color patch, S 2040-Y90R, were 50 and 50, respectively. During this 5-trial session, it was assumed that the observers did retake the perception of brightness and colorfulness of the previous reference color patch, and they were asked to remember that perception.

Then, observers had time for adapting to the main experimental settings for two minutes. This time, observers were asked to look into the lighting booth having higher illuminance on the right side of the partition in order to only adapt to the high illuminance lighting as shown in Figure 3.21. Both reference color patch and test color patch were to be placed under high illuminance lighting in this session. Observers were asked to assign a number to the brightness and colorfulness of the new reference color patch (S 1070-R20B) placed under high illuminance lighting, given the brightness and colorfulness of the previous reference color patch (S 2040-Y90R) in their memory were 50 and 50, respectively. After assigning the number to the brightness and colorfulness of the new reference color patch, observers evaluated 55 test color patches for their hue, brightness and colorfulness. The following procedures are the same as those of session 1.

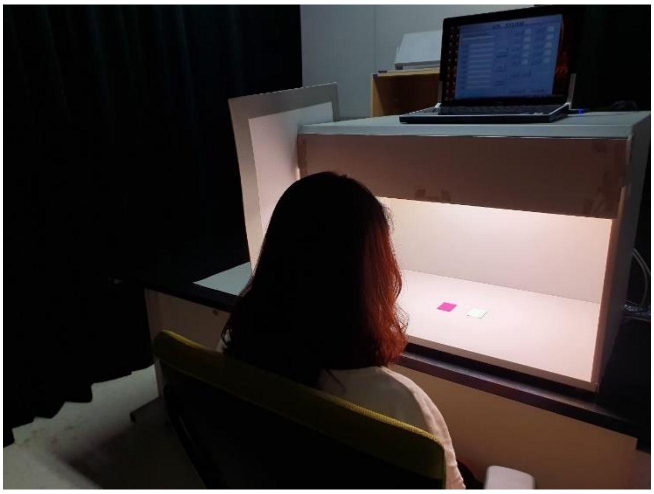


Figure 3.21 Session 2 Experimental Environment

3.8.4 Session 3 (Low Lum, Mixed Adapt)

On the fourth day, observers took part in session 3. As mentioned above, there was a need for setting the brightness and colorfulness of the new reference color patch, prior to the main experiment. Turquoise color, S 3555-B80G, was used as a reference color patch in session 3. Following the same procedure denoted in session 2, the brightness and colorfulness of the new reference color patch were set, based on the brightness and colorfulness of the reference color patch, S 2040-Y90R, used in session 1. After observers had time for retaking the perception for the previous reference patch, S 2040-Y90R, observers had time to adapt to the main experimental environment for two minutes as shown in Figure 3.22. In session 3, it was advised for observers to alternate seeing low illuminance lighting and high illuminance lighting in turns, to inhibit becoming adapted to either specific lighting. Both reference color patch and test color patch were to be placed under low illuminance lighting in this session. Thus, observers assigned new numbers to the brightness and colorfulness of the new reference color patch (S 3555-B80G) placed under low illuminance lighting, based on the brightness and colorfulness perception for the previous reference color patch, S 2040-Y90R, in their memory were 50 and 50.

After setting new numbers for the brightness and colorfulness perception for the reference color patch, observers evaluated 55 test color patches in terms of hue, brightness and colorfulness. Throughout the whole session, observers needed to alternately see both lightings, even though both the reference color patch and a test color patch were set under low illuminance lighting. The following process was the same as that of session 1 and session 2.

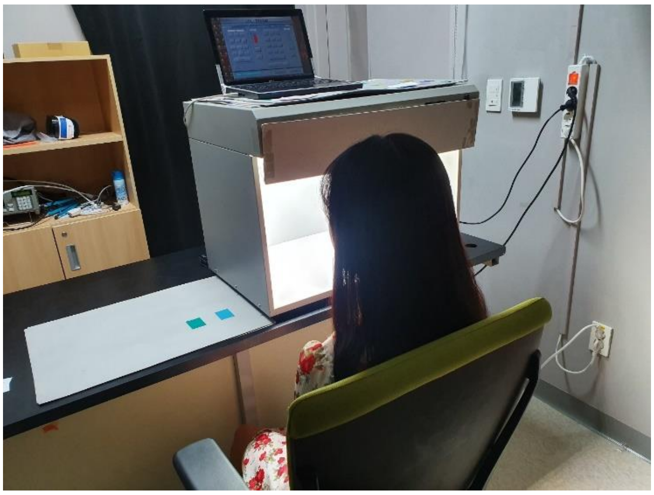


Figure 3.22 Session 3 Experimental Environment

3.8.5 Session 4 (High Lum, Mixed Adapt)

On the fifth day, session 4 was conducted. In this session, there was no need of assigning the number to the brightness and colorfulness of the new reference color patch, since the observer's adaptation to the lighting conditions and the position where the reference patch will be put were the same with those of session 3. Thus, the reference patch, S 3555-B80G, which was used in session 3 was used as the reference patch in session 4 as well. The number of brightness and colorfulness of the reference color patches pre-assigned by each observer in session 3 were also used as anchors in session 4 as well.

Therefore, observers just had time to adapt to the main experimental environment. As in session 3, observers were advised to alternate looking at both lightings so as not to adapt to one lighting as shown in Figure 3.23. In this session, since the reference color patch was put under low illuminance while the test color patches were put under high illuminance, participants naturally alternately see both lightings. 55 color patches were estimated by observers with regard to their hue, brightness and colorfulness. Other following procedures were the same as those of session 1, session 2 and session 3.

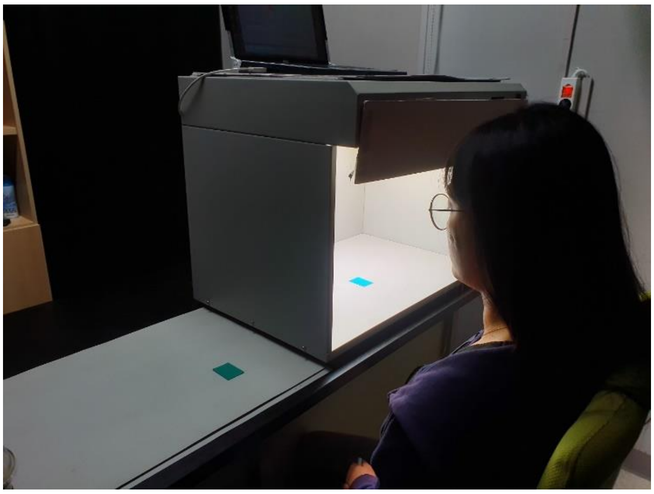


Figure 3.23 Session 4 Experimental Environment

4

Color Appearance Data Analysis Result

Chapter 4 Overview

In Chapter 4, observer performance will be evaluated whether estimating perceptual color attribute consistently throughout the experiment and whether providing reasonable estimation similar to other observers' average responses. After evaluating observer performance, averaged human color perception data regarding hue, brightness and colorfulness will be compared across sessions, based on the illuminance of lighting and the observer's adaptation to the lighting conditions. Appropriate statistical analyses will also be conducted to verify the difference or indifference among sessions.

4.1 Analysis Method

Color appearance assessment data will be averaged. The hue scale will be converted into a 0-400 scale first and then averaged. Colorfulness and brightness will be just simply averaged.

The CV analysis will be conducted so as to check whether the observer responds consistently throughout the psychophysical experiment (repeatability) and whether observer responses do not deviate from the average responses (reproducibility). The CV stands for the coefficient of variation and is useful to clarify the deviation between two data sets. The CV can be calculated, using Equation 4.1. In the equation, x denotes the first group and y denotes the second group, when there are total n trials and i simply indicates the trial index. x and y indicator for each analysis will be described later in the relevant section. The CV means the relative error when the one data set is thought of as a standard. If the two data sets were the same, the CV would be zero.

$$\mathrm{CV} = 100\left(\frac{\sum(x_i - y_i)^2}{n}\right)^{0.5} / \bar{y}$$

Equation 4.1 CV Calculation Equation

Color perception data sets will be compared across the sessions. When color perception data with regard to hue, brightness and colorfulness are compared between two different sessions, a two-sample t-test will be conducted so as to verify whether those two color perception data sets are statistically significantly different. If the difference among three or more sessions is needed to be analyzed, ANOVA will be conducted instead. T-test and ANOVA will be conducted, using Rstudio.

4.2 Observer Performance

4.2.1 Repeatability

As mentioned in section 3.5, five random color patches (S 1030-Y40R, S 1575-R10B, S 2555-B30G, S 3020-Y80R, S 3050-B20G) were presented twice in the experiment to see observers' repeatability in the experiment. By calculating the CV between trial 1 and trial 2 for each of the five color patches, it was to verify observers' response consistency. The CV values are calculated using Equation 4.1 when x indicates the trial 1 data and y indicates the trial 2 data. Calculated average CV values are described in Table 4.1. The average CV values of hue, brightness and colorfulness across all sections are 7.0, 10.6, and 13.3. These values are less than those found by Luo et al. (Luo et al., 1991) so that these CV values are tolerable. Thus, it can be said that observers who participated in this research provided consistent response throughout the sessions across hue, brightness and colorfulness domains. Also, it was shown that hue was the easiest color attribute to estimate while colorfulness was the hardest to evaluate, just as in the case found by Luo et al.

Table 4.1 Observer Repeatability

	CV (Repeatability)		
	Hue	Brightness	Colorfulness
Session 1	5.8	13.8	16.6
Session 2	8.0	6.4	11.8
Session 3	6.2	12.4	11.7
Session 4	7.9	9.9	12.9
Average	**7.0**	**10.6**	**13.3**

4.2.2 Reproducibility

Each observer's data set was compared with the average data of all observers by calculating the CV. The CV was calculated, using Equation 4.1 when x indicates individual data and y indicates average data of all observers. The CV shows how each observer's response deviates from the average data. The average CV values of all observers are shown in Table 4.2. Throughout the sessions, the CV of hue, brightness and colorfulness are 6.9, 10.2, and 12.7. Likewise in section 4.2.1, these values are tolerable as compared to the previous research done by Luo et al. (Luo et al., 1991). Therefore, it can be said that all observers gave acceptable responses as compared to the average of all so that there was no odd observer in this research. Observer repeatability and reproducibility results were similar to each other. As in repeatability result, it was found that hue was the easiest and colorfulness was the hardest color attribute to estimate.

Table 4.2 Observer Reproducibility

	CV (Reproducibility)		
	Hue	Brightness	Colorfulness
Session 1	6.1	11.9	13.8
Session 2	6.8	8.8	12.4
Session 3	7.1	10.1	12.9
Session 4	7.8	10.0	11.8
Average	**6.9**	**10.2**	**12.7**

4.2.3 Observer Performance Summary

According to the CV analysis carried out in previous sections, it was found that observer performance in both repeatability and reproducibility were tolerable as compared to the previous research conducted by Luo et al. in 1991. Thus, it has been decided to take every observer's color estimation data into account so that all observer's data will be averaged.

4.3 Color Appearance by Illuminance Level of Lighting and Observer's Adaptation Conditions

Color appearance by illuminance level of lighting and observer's adaptation conditions will be evaluated in this section.

There were two options of the position of test color patches to be placed: 1) under high illuminance lighting, and 2) under low illuminance lighting. The observer's adaptation to the lighting conditions in this experiment can be divided into two categories: 1) single lighting and 2) multiple lightings. There were two lightings having different illuminance levels so that there could be two experimental settings for a single lighting condition. Accordingly, there were three adaptation conditions in this research: 1) adapting to the low illuminance lighting only, 2) adapting to the high illuminance lighting only, and 3) adapting to both lightings while alternately seeing the two lightings.

Hue, brightness and colorfulness perception data will be compared in between the sessions having different illuminance levels and different observer's adaptation to the lighting conditions. As for the analysis of illuminance level effect on color appearance analysis, session 1 (low lum, low adapt) and session 2 (high lum, high adapt); session 3 (low lum, mixed adapt) and session 4 (high lum, mixed adapt) will be mainly discussed. Regarding the analysis of the observer's adaptation to the lighting conditions, color perception under a single lighting source and under multiple lighting sources (mixed adaptation) will be compared. Hence, session 1 (low lum, low adapt) and session 3 (low lum, mixed adapt); and session 2 (high lum, high adapt) and session 4 (high lum, mixed adapt) will be discussed.

Statistical analysis t-test and ANOVA will be conducted to see whether certain two or more visual assessment data sets are significantly different or not.

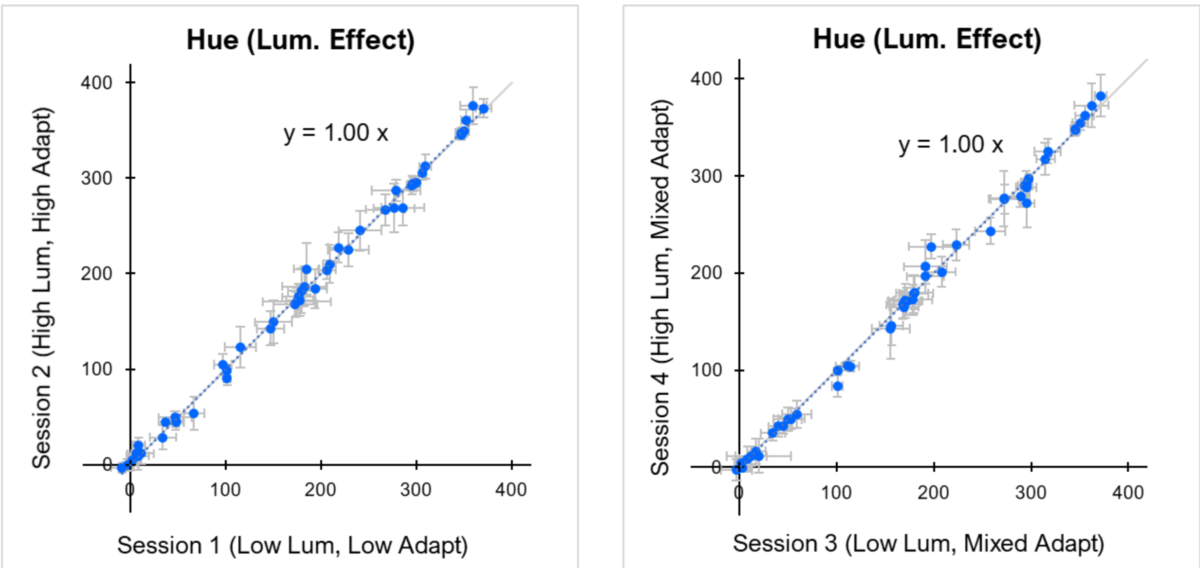
The graphs in Figure 4.1 – Figure 4.6 in the following sections show averaged visual assessment of color attributes (hue in Figure 4.1 and Figure 4.2; brightness in Figure 4.3 and Figure 4.4; and colorfulness in Figure 4.5 and Figure 4.6) of one session plotted against another session. In the graphs, 45° lines were drawn for clear comparison. In every visual data, error bars denoting the standard deviation of each data point were added.

4.3.1 Hue Appearance by Illuminance Level and Observer’s Adaptation Conditions

Figure 4.1 shows the effect of the illuminance level of lighting on the hue perception. In (a), the data points are aligned with the 45° line, which means that observers perceived hue of each color patch almost identical regardless of the adaptation illuminance levels under single lighting source, both high luminance and low luminance. In (b), similar to the result in (a), hue data points lined up on the 45° line, also referring to hue constancy without regard to luminance levels under multiple lighting sources.

In Figure 4.2, (a) and (b) show the observer’s adaptation to the lighting condition effect on the hue perception. In (a), visual hue distributes along the 45° line; thus, it can be said that the observer’s adaptation to the lighting conditions for either single lighting or multiple lightings when the patches are placed under low luminance lighting does not affect hue perception. Similarly, in (b), data points are well placed along the 45° line and it means that the hue perception is also not affected by the observer’s adaptation to the lighting conditions for neither single lighting nor multiple lightings when the test color patches are placed under high luminance lighting.

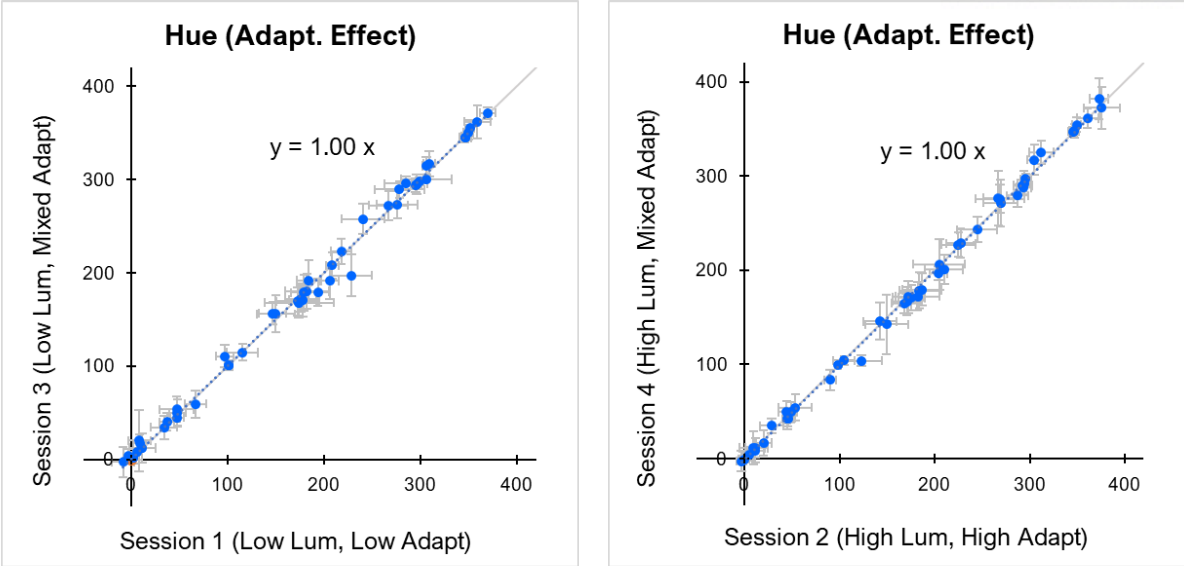
Results from Figure 4.1 indicate that illuminance level where the color patch was actually shown whether under high illuminance or under low illuminance did not affect hue perception when observers neither adapted to single lighting nor multiple lighting conditions. Through Figure 4.2, it was found that hue perception is not affected by the observer's adaptation to the lighting conditions for neither single lighting nor multiple lightings.



(a) Session 1 vs Session 2

(b) Session 3 vs Session 4

Figure 4.1 Hue Perception (Illuminance Effect)



(a) Session 1 vs Session 3 (b) Session 2 vs Session 4

Figure 4.2 Hue Perception (Observer's Adaptation Condition Effect)

According to Figure 4.1 and Figure 4.2, it was shown that there was not a big difference in hue perception with regard to the illuminance level of lightings and the observer's adaptation conditions. To verify if there wasn't any statistically significant difference among sessions, t-test and ANOVA were conducted and the results were described in Table 4.3 and Table 4.4. According to Table 4.3, it was found that there was no significant difference between session 1 and session 2; session 3 and session 4; session 1 and session 3; and session 2 and session 4 when it comes to hue perception. Also, ANOVA results in Table 4.4 shows that there is no significant difference in hue perception even when all sessions are compared among one another. Thus, it can be said again that hue perception is not affected by illuminance level of lighting either under single lighting condition or multiple lighting conditions, and by illuminance level and observer's adaptation to the lighting condition for neither single lighting nor multiple lightings.

In the previous research having similar experimental conditions to this research (under two lightings having largely different illuminance levels (100 cd/m^2, 4700 cd/m^2)), significant hue shifts were found: red colors and green colors appeared to be bluish in the magnitude of 2.5-3.9 and 5.0-6.9, respectively (Hwang et al., 2019). Observations of hue shifts in the previous study having similar experimental settings indicate that hue appearance might have been affected by the illumination level of lighting or the observer's adaptation to the lighting conditions. Different results from previous and current experiments may be due to differences in experimental methodologies (color matching in the previous study; magnitude estimation in the current study), or due to other factors. Additional verification experiments are needed to clarify the reasons behind that.

Table 4.3 t-test Result in Hue Domain

Compared Sessions		t-value	*p*
1	2	0.152	0.880
3	4	0.477	0.634
1	3	0.323	0.747
2	4	-0.010	0.992

*$p < .05$

Table 4.4 ANOVA Result in Hue Domain

Compared Sessions				Df	F-value	*p*
1	2	3	4	3	0.035	0.991

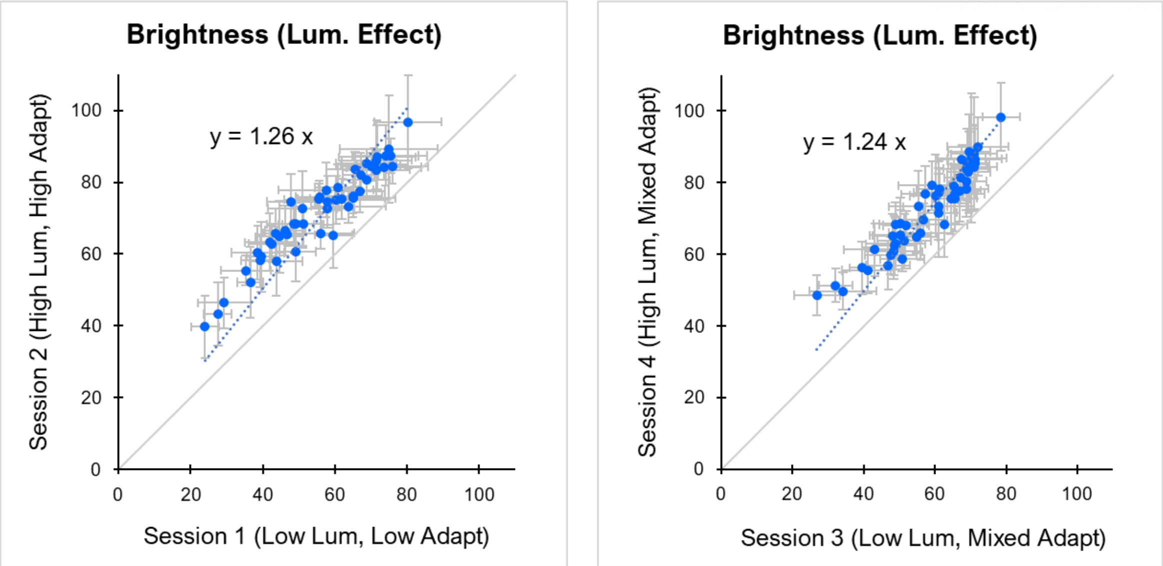
*$p < .05$

4.3.2 Brightness Appearance by Illuminance Level and Observer's Adaptation Conditions

Figure 4.3 shows averaged brightness visual assessment data between sessions having different illuminance levels of lightings. In (a), the data points are placed above 45° line which means the color patch appears to be 26% brighter under higher illuminance condition when observers adapt to a single lighting source. Similar to the result in (a), graph (b) shows visual brightness data points are plotted above 45° line as well. It means that the color patches look 24% brighter under higher illuminance under multiple lighting conditions.

In Figure 4.4, (a) and (b) illustrate the effect of the observer's adaptation to the lighting conditions — for either single lighting or multiple lightings — on brightness perception. In (a), visual brightness data points are aligned with the 45° line. Thus, the color patches appeared to be almost of the same brightness under single low illuminance lighting and under multiple lightings when the color patches placed under low illuminance lighting. Technically saying, color patches look 2% brighter under mixed adaptation conditions than under a single low illuminance lighting. Similarly, (b) shows that the visual brightness data points are also placed on the 45° line, indicating brightness perception is not affected by whether observer adapts to a high illuminance lighting or under multiple lightings when the color patches are shown under high illuminance lighting.

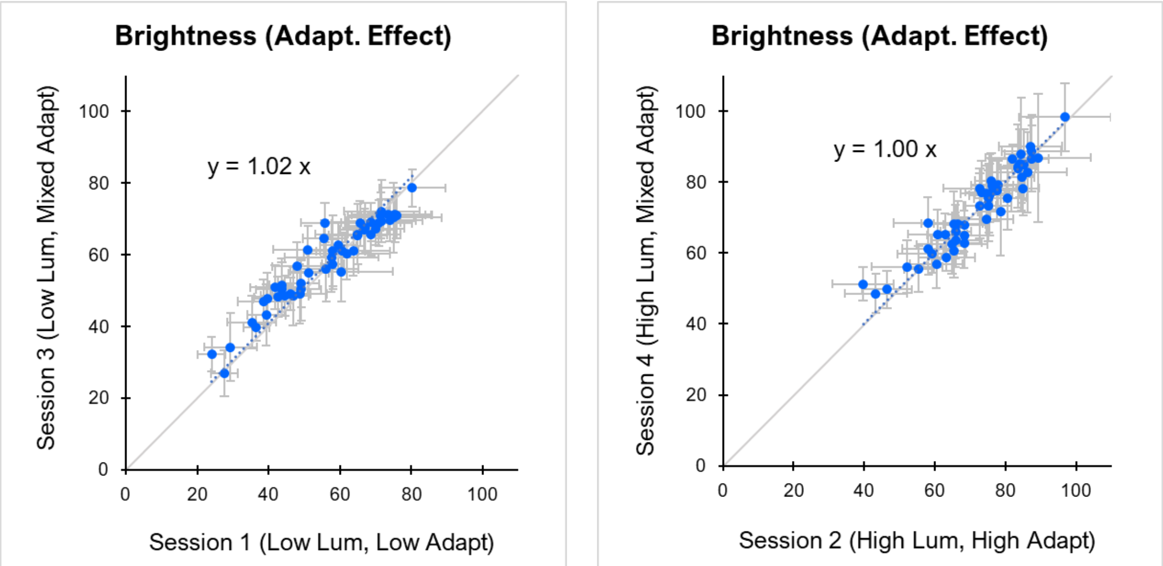
In Figure 4.3, it can be said that brightness perception is affected by the illuminance of lighting. To be specific, color patches look brighter when the test color patches are placed under higher illuminance lighting regardless of observer adapting to a single lighting source and to multiple lighting sources. Given the results shown in Figure 4.4, it can be said whether the observer adapts to a single lighting source or to multiple lighting sources did not affect brightness perception, implying observers locally adapted to the lighting where the colors were directly shown.



(a) Session 1 vs Session 2

(b) Session 3 vs Session 4

Figure 4.3 Brightness Perception (Illuminance Effect)



(a) Session 1 vs Session 3

(b) Session 2 vs Session 4

Figure 4.4 Brightness Perception (Observer's Adaptation Condition Effect)

According to Figure 4.3 and Figure 4.4, it was shown that there was a difference caused by the illuminance level while no difference was caused by the observer's adaptation conditions in brightness perception. To verify these results statistically, a t-test was conducted, and the results are shown in Table 4.5. As a result, it was discovered that brightness perception data of session 1 and session 2; and session 3 and session 4 are significantly different. Session 1 and session 3; and session 2 and session 4 are not significantly different as expected. Thus, it is verified that the illuminance level does affect brightness perception while the observer's adaptation to the lighting condition has no influence on brightness perception.

Table 4.5 t-test Result in Brightness Domain

Compared Sessions		t-value	*p*
1	2	-6.588	*0.000
3	4	-6.629	*0.000
1	3	-0.891	0.375
2	4	-0.117	0.907

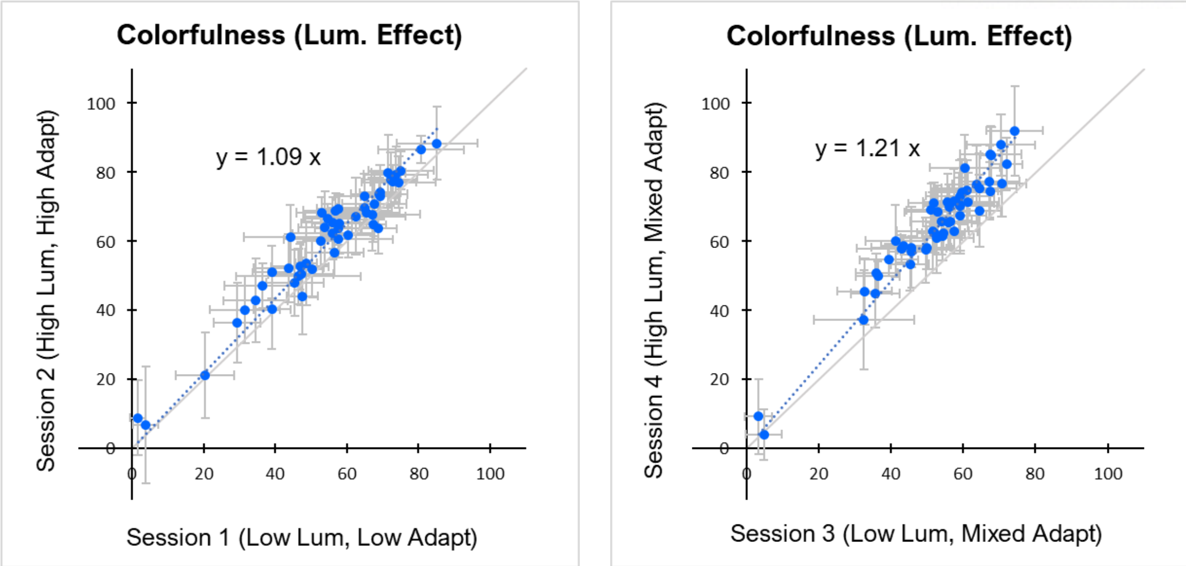
*$p < .05$

4.3.3 Colorfulness Appearance by Illuminance Level and Observer's Adaptation Conditions

Figure 4.5 shows averaged colorfulness visual estimation data between sessions according to the illuminance level of lighting. In (a), colorfulness perception data points are plotted slightly above 45° line, indicating that the color patches appear to be 9% more colorful to some extent under higher illuminance lighting when observers adapt to a single lighting source. Also, in (b), colorfulness perception data points are placed above 45° line, which means the color patch looks 21% more colorful under when it is placed under higher illuminance lighting, observer adapting to multiple lighting conditions. The results that color looks more colorful under higher illuminance corresponds to the Hunt effect described in section 2.3.3.

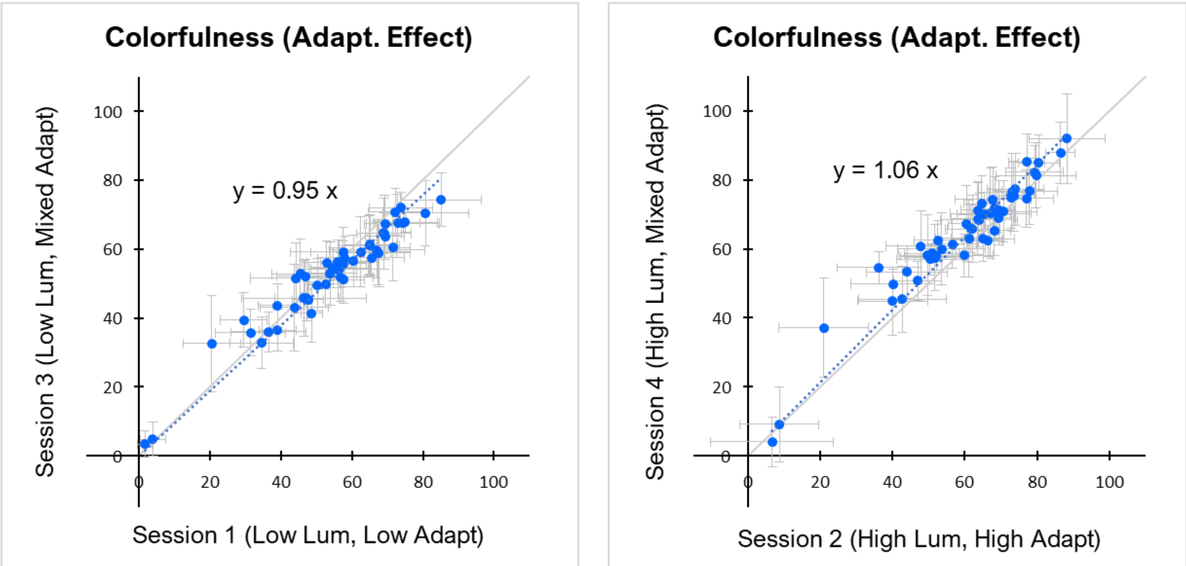
In Figure 4.6, (a) and (b) were to illustrate the influence of the observer's adaptation to the lighting conditions on colorfulness perception. In (a) and (b), visual colorfulness under a single lighting source and under multiple lighting sources were compared. In (a), the data points are slightly below the 45° line, but the general trend of the graph is that the data points are on the line. It means colorfulness perception is not that affected by the observer's adaption to the lighting conditions neither under low illuminance lighting nor under mixed adaptation conditions (alternately seeing two lightings) when the test color patches are placed under low illuminance lighting. Technically saying, the color looks 5% more colorful under a single low illuminance lighting than under multiple lightings. In (b), the data points are slightly above the 45° line, but the general trend is that the points are on the line. It means that colorfulness perception is not that affected by the observer's adaptation to the lighting conditions when the test color patches are placed under higher illuminance lighting. Strictly speaking, color appears to be 6% more colorful under mixed adaptation conditions than under a single high illuminance lighting.

Through Figure 4.5, it is shown that color patches look more colorful under higher illuminance lighting regardless of observer adapting lighting conditions whether observer adapts to a single lighting source or to multiple lighting sources. The results that Figure 4.6 shows are colorfulness constancy can be found regardless of the observer's adaptation to the lighting conditions, implying observers locally adapted to the lighting where the colors were directly shown.



(a) Session 1 vs Session 2 (b) Session 3 vs Session 4

Figure 4.5 Colorfulness Perception (Illuminance Effect)



(a) Session 1 vs Session 3 (b) Session 2 vs Session 4

Figure 4.6 Colorfulness Perception (Observer's Adaptation Condition Effect)

In Figure 4.5, it was shown that there was a difference caused by the illuminance level in colorfulness perception. In Figure 4.6, it was found that there was no big difference in colorfulness perception caused by the observer's adaptation to the lighting conditions when the test color patches are either placed under low illuminance lighting or high illuminance lighting. However, there was a slight difference in colorfulness appearance in both conditions. In order to see if these differences or indifferences are statistically significant, a t-test was conducted, and the results are summarized in Table 4.6. As a result, there was a statistically significant difference between session 3 and session 4 but there was no significant difference between session 1 and session 2. Statistically, it means the color looks more colorful under higher illuminance only when observers adapted to multiple lighting conditions. Also, it turned out that colorfulness perception was not significantly different between single lighting (both low illuminance and high illuminance) conditions and multiple lighting conditions.

Table 4.6 t-test Result in Colorfulness Domain

Compared Sessions		t-value	*p*
1	2	-1.797	0.075
3	4	-4.173	*0.000
1	3	0.643	0.521
2	4	-1.326	0.188

*$p < .05$

Chapter 4 Summary

Observer performance in estimating color appearance was evaluated by the CV analysis. As a result, observer average repeatability was 7.0, 10.6 and 13.3; and observer average reproducibility was 6.9, 10.2 and 12.7 for hue, brightness and colorfulness, respectively. Observers who participated in this research provided reasonable color appearance estimation as compared to the previous study conducted by Luo et al. in 1991.

Averaged human color perception data regarding hue, brightness and colorfulness were compared across sessions, based on the illuminance of lighting and the observer's adaptation to the lighting conditions. As a result, illuminance level where the color was actually shown whether under high illuminance or under low illuminance did not affect hue perception when observers neither adapted to single lighting nor multiple lighting conditions. In addition, it was found that hue perception is not affected by the observer's adaptation to the lighting conditions for neither single lighting nor multiple lightings. The findings were supported by statistical analyses. Brightness perception is affected by the illuminance of lighting. The color looks brighter when the test color is placed under higher illuminance lighting regardless of observer adapting to a single lighting source and to multiple lighting sources. However, whether the observer adapts to a single lighting source or to multiple lighting sources did not affect brightness perception, implying observers locally adapted to the lighting where the colors were directly shown. These findings were supported by statistical analyses. Lastly, as for colorfulness perception, the color looks more colorful under higher illuminance lighting either under single lighting or under multiple lightings. However, colorfulness constancy can be found regardless of the observer's adaptation to the lighting conditions for either single lighting or multiple lightings, implying local adaptation has occurred as shown in brightness perception result. The findings were partly supported by statistical analyses.

5

CIECAM02 Model Performance Evaluation

Chapter 5 Overview

In Chapter 5, the CIECAM02 color appearance model performance will be evaluated under single and multiple lighting conditions, when it is compared to color perception data. Hue perception data will be compared with factor H (hue quadrature); brightness with factor Q (brightness); and colorfulness with factor M (colorfulness).

It might be more appropriate to take advantage of the Retinex theory algorithm described in section 2.7 or the iCAM06 model explained in section 2.8 for color appearance prediction under complicated adaptation conditions as in the experimental condition of this research. However, these two models are algorithms that are mainly used for image processing technology, so they might not be suitable for this experimental environment. Therefore, in this study, although limited, the CIECAM02 model developed under the assumption that the observer is adapted to one white, as shown in section 2.6, is used to predict color appearance in multiple lighting conditions.

The CV analysis will be conducted to see deviation between color appearance assessment data and the model prediction data.

5.1 Parameter Setting for CIECAM02 Calculation

CIECAM02 input parameters denoted in section 2.6 were set for each session. The absolute CIE XYZ values of the test color patches and the reference white patches used in the CIECAM02 calculation were described in Appendix 2, which were measured by the spectroradiometer (CS-2000, Minolta) in actual experimental scenes. The absolute CIE XYZ values were firstly converted into a relative scale based on the absolute luminance of the reference white (L_w) and then used in the calculation.

In all sessions, viewing condition parameters (c, N_c, F) were set to be average. In session 1 and session 3, CIE XYZ values of the test color patches under low illuminance lighting were used while those under high illuminance lighting were used for session 2 and session 4 calculation. As for the reference white, the white patch under low illuminance lighting was selected for the reference white for session 1 and session 3, and that under high illuminance lighting was chosen for the reference white for session 2, session 3 and session 4. In section 4.3, it turned out that visual assessment data for color attributes of session 1 and session 3 showed no significant difference. It means the observer's adaptation to the lighting conditions for either single lighting or multiple lightings has no significant effect on human color perception. Thus, both white patch under low illuminance and under high illuminance were used for the CIECAM02 calculation for session 3, assuming local adaptation and global adaptation, respectively. As described in section 2.6.3, the luminance of adapting field (L_A) was set to 20% of the luminance of the reference white (L_w). Likewise, the relative luminance of background (Y_b) was set to 20% of the relative luminance of white. The factor D, the degree of adaptation, was set, following the equation in section 2.6.3. Detailed values for input parameters are shown in Table 5.1.

Table 5.1 Input Parameters for CIECAM02 Calculation

	X_w	Y_w (cd/m^2)	Z_w	L_A (cd/m^2)	D	Y_b	c	N_c	F
Session 1	85.96	93.12	82.38	18.62	0.856	20.00	0.69	1.00	1.00
Session 2	1546.52	1680.63	1420.85	336.13	0.995	20.00	0.69	1.00	1.00
Session 3 (Global)	1546.52	1680.63	1420.85	336.13	0.995	20.00	0.69	1.00	1.00
Session 3 (Local)	85.96	93.12	82.38	18.62	0.856	20.00	0.69	1.00	1.00
Session 4	1546.52	1680.63	1420.85	336.13	0.995	20.00	0.69	1.00	1.00

5.2 CIECAM02 H Performance

Figure 5.1 shows hue perception data plotted against CIECAM02 hue prediction data H. In the figure, the x-axis indicates H and the y-axis denotes hue perception. In every visual data in the graph, along the y-axis, error bars denoting the standard deviation of each data point were added. For a clear comparison between hue perception data and hue prediction data, the 45° line was drawn in every graph.

In Figure 5.1, data points for each session are well aligned with the 45° line. It means the CIECAM02 H data substantially coincide with the hue perception data in every experimental condition. In addition, the figure shows that all graphs overlapped with one another, showing hue prediction data are similar across the sessions as well as hue perception data. Also, the global adaptation trial and local adaptation trial of session 3 have no significant difference.

In the figure, it is shown that the shape of the graph appears like a staircase. In the 100-150 (yellow-yellowish green), 150-200 (yellowish-green), and 250-300 (cyan-blue) sections of the H value, the hue perception values are maintained in a straight line with little change. This shows that observers were responding categorically, not sensitively to hue changes in those ranges.

Table 5.2 shows the CV analysis between hue perception data in each session and CIECAM02 prediction H data, using Equation 4.1. In this case, x denotes hue assessment data and y denotes H data in the equation. The CV values across the sessions are ranged between 7.3 and 9.0, which can be said to be tolerable so that the hue perception data and CIECAM02 H data have a high correlation.

In summary, CIECAM02 hue prediction data H substantially coincides with the hue perception data regardless of the illuminance level of the lighting (either high or low) and the observer's adaptation to the lighting conditions (for either single lighting or multiple lightings).

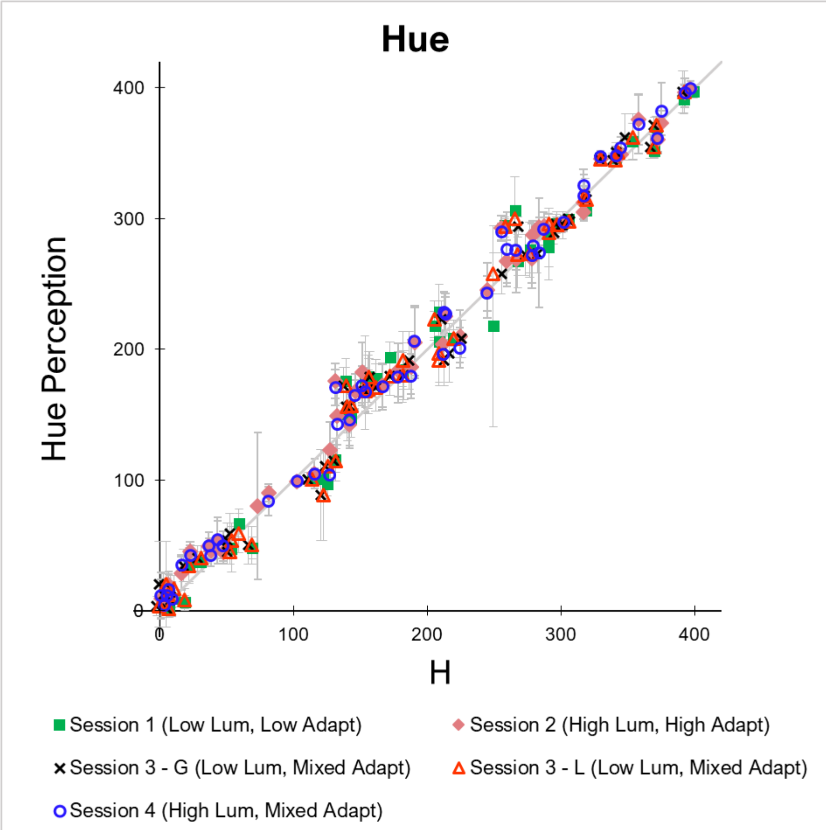


Figure 5.1 CIECAM02 H Performance

Table 5.2 CV Analysis Result between Hue Perception and CIECAM02 H

Compared Data Set		CV
Session 1	H	8.0
Session 2	H	7.3
Session 3 (Global)	H	7.6
Session 3 (Local)	H	7.6
Session 4	H	9.0

5.3 CIECAM02 Q Performance

The scale of CIECAM02 brightness prediction Q and brightness perception data are not the same since brightness perception data has no maximum limit. Thus, a constant was multiplied to the calculated Q of session 1 to make the average value the same as that of brightness perception data in session 1. Then, the same constant was multiplied to the calculated Q of all other sessions.

Figure 5.2 shows brightness perception data plotted against the rescaled CIECAM02 Q. In the figure, the x-axis denotes Q and the y-axis indicates brightness perception. Error bars depicting standard deviation were added to each brightness data point along the y-axis. A 45° line was added to every graph for a clear comparison between two data sets. Figure 5.3 shows graphs describing the Q data and the brightness perception data session by session, and the linear regression line and its equation have been added.

Table 5.3 shows the CV values between the brightness perception data and CIECAM02 Q. Equation 4.1 was used for calculating the CV value when x denotes brightness perception data and y denotes Q data in the equation. The CV value of session 1 is 9.1. The CV value of session 3 (global) is 27.6 while session 3 (local) is 7.2. The CV value of session 2 and session 4 are around 30. From the CV analysis, it was found that the CIECAM02 brightness prediction performance is quite tolerable in session 1 and session 3 (local), having a high correlation with brightness perception data. However, the model was found to need modification in Q calculating process, having large disparities with brightness perception data under high illuminance both under single lighting and multiple lighting conditions as shown in the CV values of session 2 and session 4.

In Figure 5.2, data points for session 1 and session 2 should be in line since they are both under single lighting conditions. Specifically, data points for session 2 with high illuminance lighting should be placed upper right side of those for session 1 with low illuminance lighting. In Figure 5.3 (a), looking at the brightness perception data and Q data of session 2 compared to session 1, it is shown that the Q data is 56% overestimated compared to brightness perception data. Thus, a modification of the Q calculation process is needed under higher illuminance in a single lighting condition.

In Figure 5.2, it can be seen that the session 3 (global) data points are placed left upper side of the session 1 data points while those of session 3 (local) are well aligned with session 1 data points. Alignment with session 1 and session 3 (local) supports the findings in section 4.3.2 that the brightness perception was not affected by the observer's adaptation to the lighting conditions for neither single lighting nor multiple lightings. Specifically, as seen in Figure 5.3 (d), Q data of session 3 (global) compared to session 1 20% underestimate compared to brightness perception data. As seen in Figure

5.3 (e), when the observer local adaptation was assumed in session 3, the disparity was reduced to 2% as compared to the global adaptation case as shown in (d).

In Figure 5.2 (b), Q data of session 4 compared to session 3 (global) almost overestimate twice that of brightness perception data. In session 3 (local) case described in Figure 5.2 (c), the deviation is reduced to 58% but it was found that the CIECAM02 model still overestimated Q compared to brightness prediction data. Thus, the calculation process of the Q indicator needs modification when it comes to predicting under high illuminance lighting in multiple lighting conditions as in session 4.

Figure 5.2 and Figure 5.3 (f) show the relationship of Q data and brightness perception between session 2 and session 4. First, session 2 and session 4 have the same CIECAM02 Q data. This is because it was assumed that the observer adapted to the white patch under high illuminance lighting whose luminance was the highest in the scene in session 2 and session 4. In Figure 5.2, data points of session 2 and session 4 were found to be overlapped with each other. Also, in Figure 5.3 (f), the Q data and brightness perception data of session 4 compared to session 2 showed almost perfect agreement. In the paragraphs above, it was decided to adjust the Q factor calculation process of session 2 and session 4, but if they were adjusted to similar levels in both sessions, they would have little impact on the trend of the graph.

To sum up, Q is 56% overestimated under high illuminance than under low illuminance under single lighting. Under multiple lighting conditions, Q is 58% overestimated under high illuminance than under low illuminance. Thus, the Q calculation parameter should be modified so as not to overestimate under higher illuminance. When local adaptation is assumed in mixed adaptation conditions with the color shown under low illuminance, the Q prediction performance is increased by 18 – 39%.

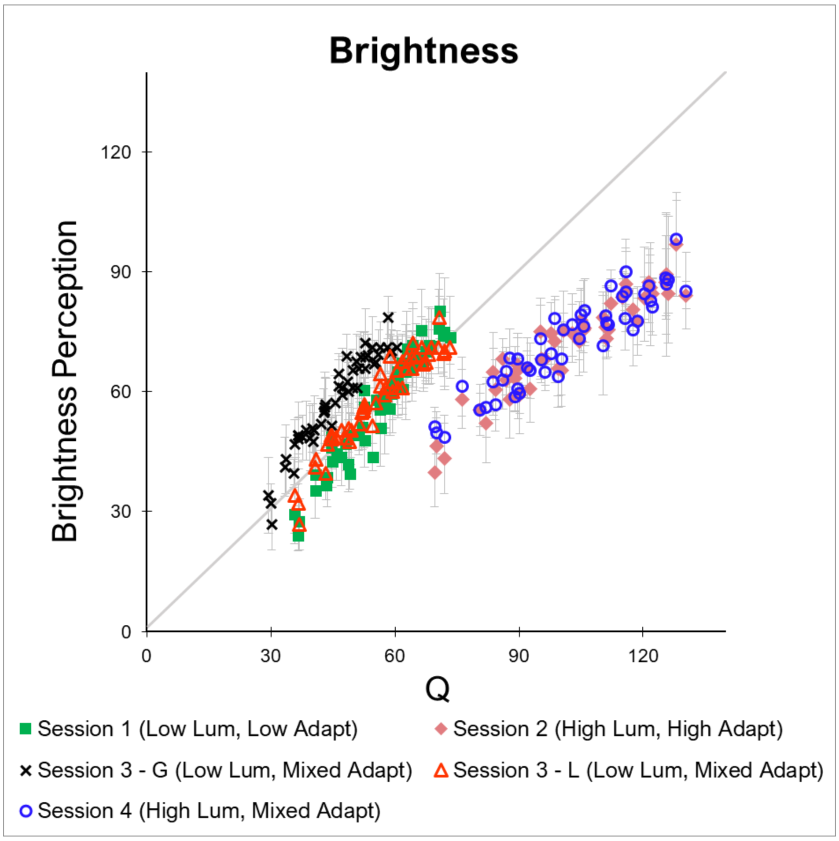
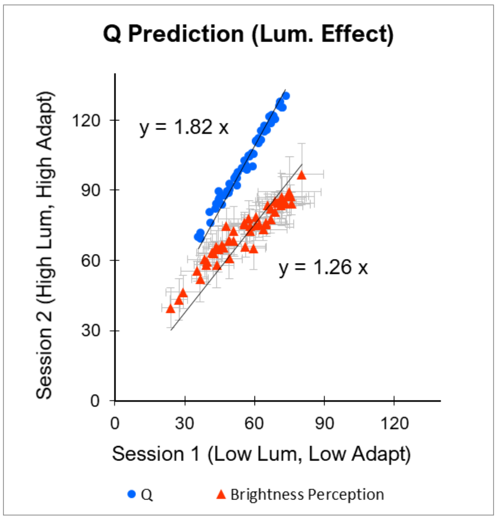


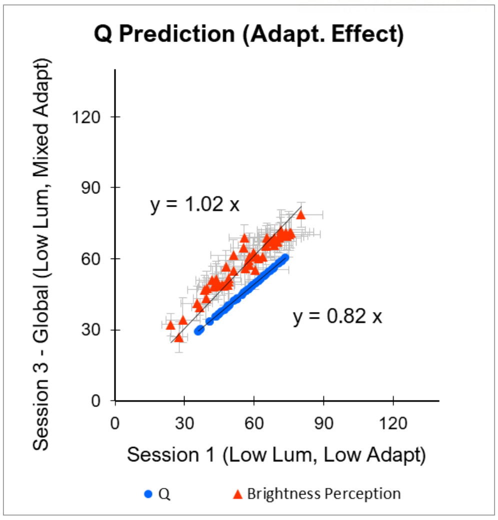
Figure 5.2 CIECAM02 Q Performance

Table 5.3 CV Analysis Result between Brightness Perception and CIECAM02 Q

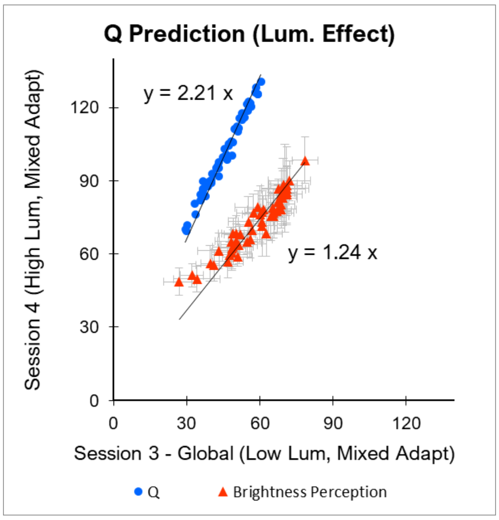
Compared Data Set		CV
Session 1	Q	9.1
Session 2	Q	30.1
Session 3 (Global)	Q	27.6
Session 3 (Local)	Q	7.2
Session 4	Q	29.7



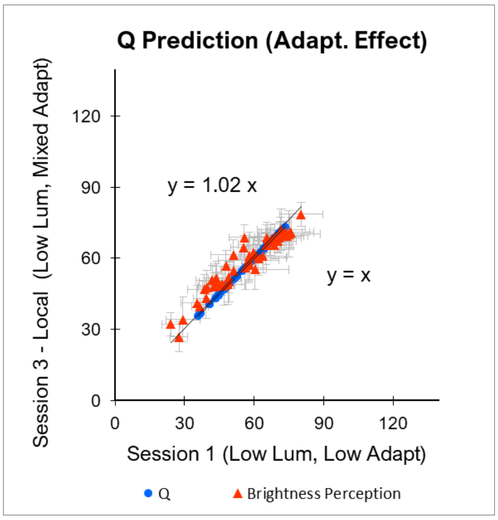
(a) Session 1 vs Session 2



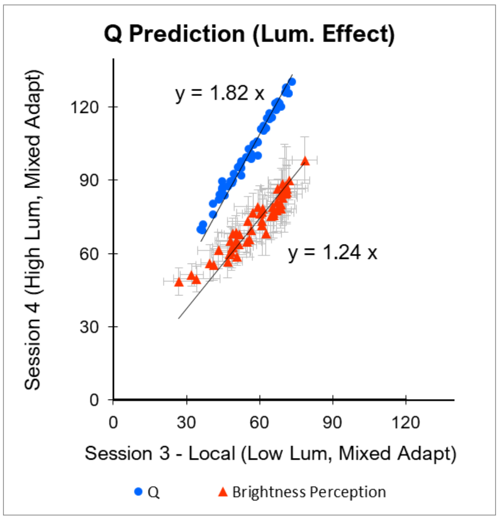
(d) Session 1 vs Session 3 (Global)



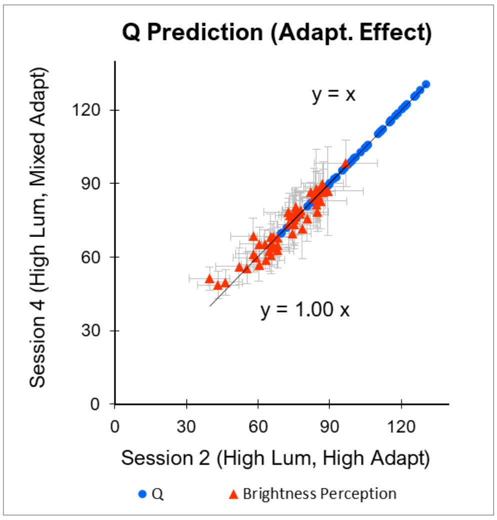
(b) Session 3 (Global) vs Session 4



(e) Session 1 vs Session 3 (Local)



(c) Session 3 (Local) vs Session 4



(f) Session 2 vs Session 4

Figure 5.3 CIECAM02 Q vs Brightness Perception

5.4 CIECAM02 M Performance

The scale of CIECAM02 colorfulness prediction M data and that of colorfulness perception data are not the same because colorfulness perception estimation was carried out without maximum limit. Therefore, a constant, which makes the average value of M data of session 1 the same with that of colorfulness perception data of session 1, was multiplied to the calculated M data. The same constant was also multiplied to the calculated M prediction data of all other sessions.

Figure 5.4 describes colorfulness perception data plotted against the rescaled CIECAM02 M. In the figure, the x-axis indicates M while the y-axis denotes colorfulness perception data. Along the y-axis, error bars were added to every data point, denoting standard deviation. 45° line was added to every graph for a clear comparison between two data sets. Figure 5.5 shows M data and colorfulness perception data for one session compared to another session.

Table 5.4 shows the CV values between the colorfulness perception data and CIECAM02 M data. Equation 4.1 was used to calculate the CV values. In this case, x denotes colorfulness perception data and y indicates M data in the equation. The CV value of session 3 (global) is 73.3 while that of session 3 (local) is 23.9. The CV value of session 1, session 2, session 3 (local) and session 4 is ranged from 19.7 to 23.9. This range does not mean a good agreement between the model colorfulness prediction data and colorfulness perception data. In the observer performance evaluation section 4.2, observers were found to have the most difficulty with colorfulness evaluation. Compared to that, it might not be that much disparity.

In Figure 5.4, it was found that the data points of session 2 are placed under the 45° line, which means the model overestimates the colorfulness M factor as compared to the colorfulness perception data. Specifically, in Figure 5.5 (a), M data of session 2 compared to session 1 is 10% overestimating as compared to the colorfulness perception data of session 2 compared to session 1.

Figure 5.4 shows that data points of session 3 (global) is placed left upper side of session 1 while session 3 (local) data points are overlapped with session 1 data points, supporting the findings in section 4.4.3 that colorfulness perception was not different despite different observer's adaptation condition (neither single lighting nor multiple lightings). Figure 5.5 (d) shows the M data of session 3 (global) against session 1 about twice underestimate as compared to colorfulness perception data. When the local adaptation is applied to session 3 as shown in Figure 5.5 (e), the disparity with colorfulness perception data is reduced to 5 %.

In Figure 5.5 (b), M data of session 4 against session 3 (global) almost twice overestimate as compared to colorfulness prediction data under multiple lightings. In Figure 5.5 (c), M data of session 3 (local) against session 4 was found to 2% underestimate as compared to colorfulness perception data, showing performance has been far increased after observer local adaptation was applied.

Since session 2 and session 4 have the same input parameters for calculating CIECAM02 M, the output M values are the same. In section 4.4.3, there was no difference in colorfulness perception under single lighting and multiple lightings. Thus, Figure 5.4 shows that data points for session 2 and session 4 are well aligned. In Figure 5.5 (f), M data of session 4 against session 2 only 6% underestimate as compared to colorfulness perception data. If the adjusted Q calculation factor of session 2 and session 4 to have similar value, they would have little change in the trend of M data compared to colorfulness perception.

All in all, M is 10% overestimated under high illuminance than under low illuminance under single lighting. Thus, the M calculation parameter should be modified so as not to overestimate under higher illuminance. When local adaptation is assumed in mixed adaptation conditions with the color shown under low illuminance, the M prediction performance is increased by 44 – 88%.

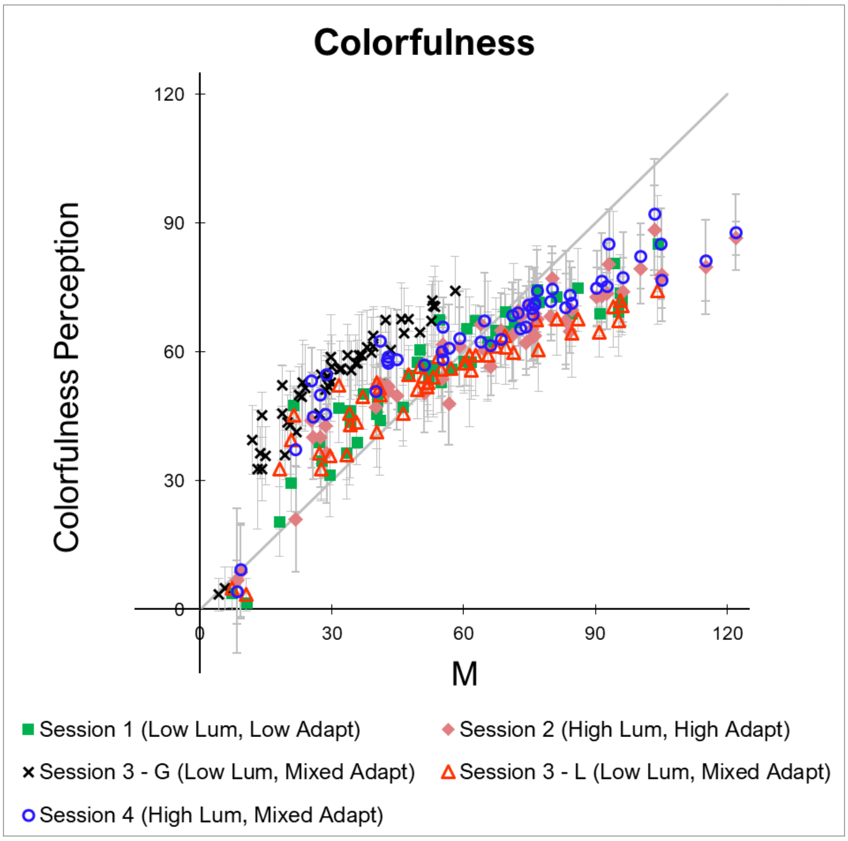
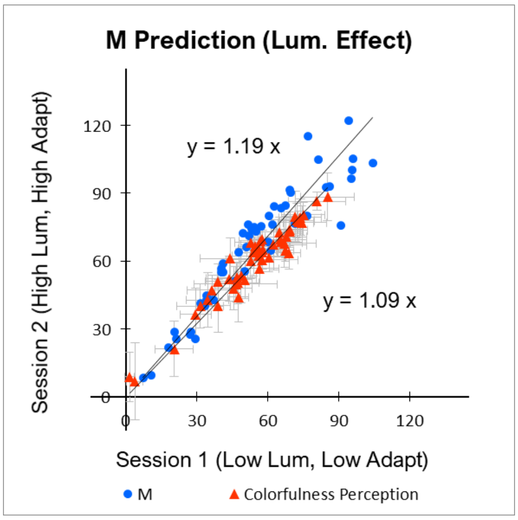


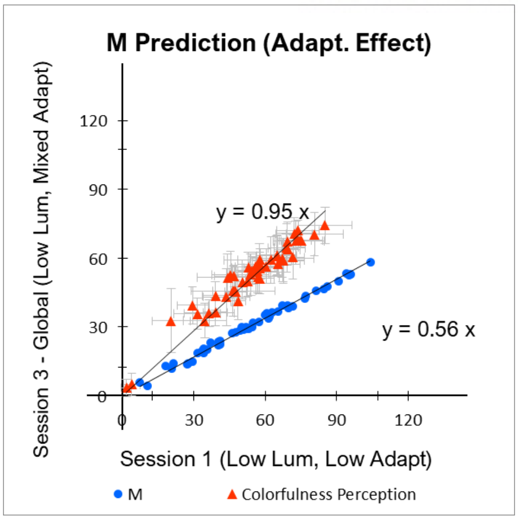
Figure 5.4 CIECAM02 M Performance

Table 5.4 CV Analysis Result between Colorfulness Perception and CIECAM02 M

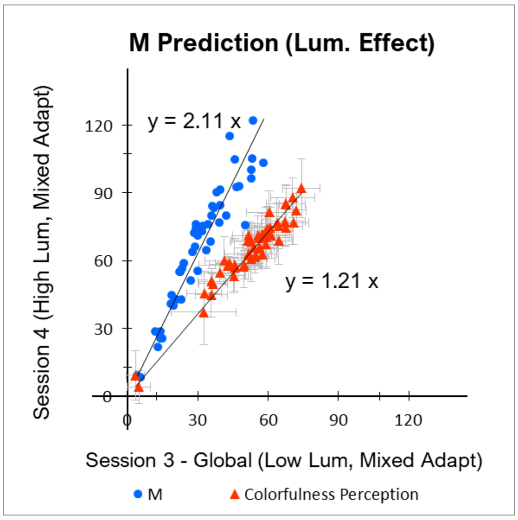
Compared Data Set		CV
Session 1	M	19.7
Session 2	M	21.3
Session 3 (Global)	M	73.3
Session 3 (Local)	M	23.9
Session 4	M	22.1



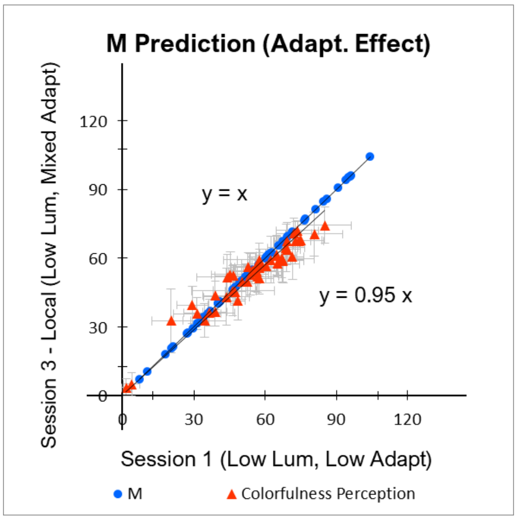
(a) Session 1 vs Session 2



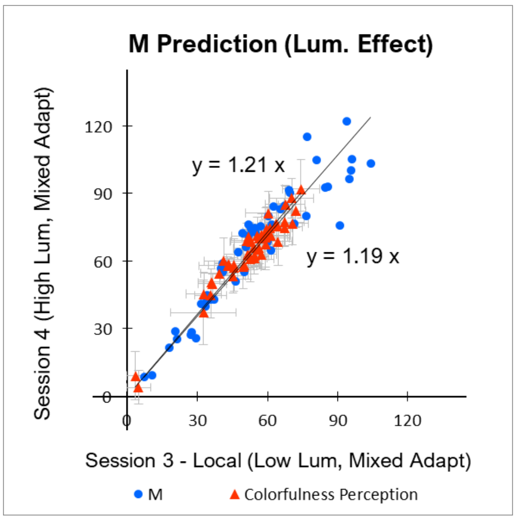
(d) Session 1 vs Session 3 (Global)



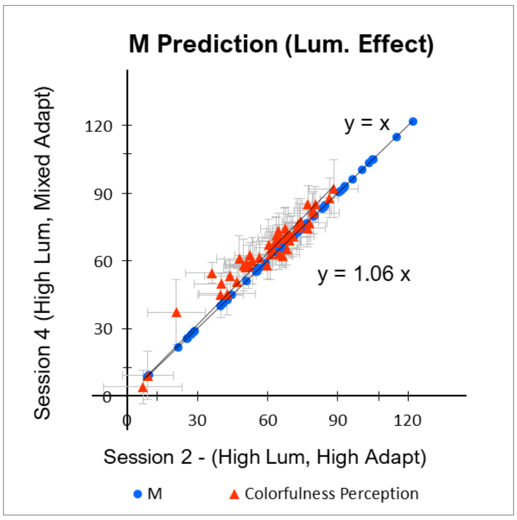
(b) Session 3 (Global) vs Session 4



(e) Session 1 vs Session 3 (Local)



(c) Session 3 (Local) vs Session 4



(f) Session 2 vs Session 4

Figure 5.5 CIECAM02 M vs Colorfulness Perception

Chapter 5 Summary

The color appearance model CIECAM02 performance was evaluated in terms of hue, brightness and colorfulness by comparing model prediction data with color perception data.

CIECAM02 hue prediction data H adeptly coincide with the hue perception data regardless of the illuminance level of the lighting either high or low, and the observer's adaptation to the lighting conditions for either single lighting or multiple lightings. As for brightness prediction performance of the CIECAM02, Q is 56% overestimated under high illuminance than under low illuminance under single lighting. Under multiple lighting conditions, Q is 58% overestimated under high illuminance than under low illuminance. Thus, the Q calculation parameter should be modified so as not to overestimate under higher illuminance. When local adaptation is assumed in mixed adaptation conditions with the color shown under low illuminance, the Q prediction performance is increased by 18 – 39%. Regarding the colorfulness prediction performance of the model, M is 10% overestimated under high illuminance than under low illuminance under single lighting. Thus, the M calculation parameter should be modified so as not to overestimate under higher illuminance. When local adaptation is assumed in mixed adaptation conditions with the color shown under low illuminance, the M prediction performance is increased by 44 – 88%.

All findings are supported by the CV values calculated between color perception data and model prediction data.

6

CIECAM02 Model Modification

Chapter 6 Overview

In Chapter 5, the prediction performance of hue, brightness and colorfulness of CIECAM02 was evaluated. As a result, it was found that brightness prediction indicator Q was overestimated as compared to the brightness perception data under higher illuminance condition both under single lighting and multiple lightings, 56% and 58%, respectively. Also, colorfulness prediction indicator M was 10% overestimated as compared to the colorfulness assessment data under higher illuminance conditions under single lighting while there was no significant difference found under lower illuminance lighting. In Chapter 6, there will be a modification in parameters for the CIECAM02 Q and M calculation equation.

As described in section 2.6.12 and 2.6.14, the CIECAM02 Q and M calculation equations are as below:

$$Q = \left(\frac{4}{c}\right)\sqrt{\frac{J}{100}}(A_W + 4)F_L^{0.25} \;, \qquad M = CF_L^{0.25}$$

The two indicators have a parameter in common, the luminance-level adaptation factor, F_L. It was assumed that lowering the value of F_L would help Q and M not to be overestimated. Thus, the F_L factor will be modified to improve the CIECAM02 performance in the brightness and colorfulness prediction in this section. The F_L factor itself will be discussed in the following section 6.1.

6.1 Luminance-level Adaptation Factor (F_L)

As described in 2.3.4, once the observer fully adapts to a certain condition, the observer tends to discount the illumination color and illumination level when perceiving the color of an object. The luminance-level adaptation factor, F_L, is a factor for the model adaptation to changes in the level of the illumination. The factor F_L is expressed as a function of the absolute luminance of adapting luminance, L_A as described in 2.6.5. The equation for the factor F_L is the following.

$$F_L = 0.2k^4(5L_A) + 0.1(1 - k^4)^2(5L_A)^{\frac{1}{3}}$$

$$\text{where } k = 1/(5L_A + 1)$$

In Figure 6.1, the blue line shows the graph of the log of the factor F_L plotted against the log of $5L_A$. The graph was plotted based on the equation of calculating the F_L described above. In Table 6.1, the calculated values of F_L and the log of the F_L; and L_A and the log of the $5L_A$ under high illuminance lighting and low illuminance lighting are described, respectively. These calculated values are also denoted in Figure 6.1 with yellow dotted lines.

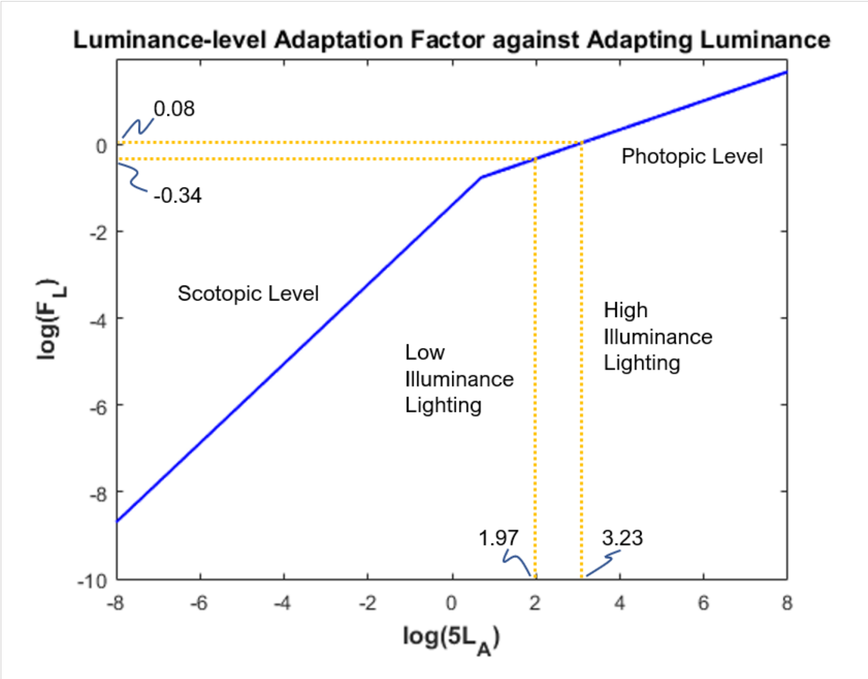


Figure 6.1 F_L against L_A

Table 6.1 F_L and L_A under High Lum. & Low Lum. Lightings

	High Illuminance Lighting	Low Illuminance Lighting
L_A (cd/m^2)	336.13	18.62
log($5L_A$)	3.23	1.97
F_L	1.20	0.46
log(F_L)	0.08	-0.34

6.2 Luminance-level Adaptation Factor (F_L) Modification

It will be attempted to lower the value of the luminance level of adaptation factor F_L to compensate for the overestimation of the brightness under high illuminance in single lighting and multiple lightings conditions and colorfulness under single lighting, specifically in session 2 and session 4. The factor F_L was optimized to make the CV value calculated between brightness perception data and Q data the smallest, which means the disparity between perception and prediction data became minimal. The initial F_L value was set to 1.20 as a result of calculation through the F_L calculation equation denoted in section 6.1, but later adjusted to 0.67 as a result of the optimization process. The calculated CV values after modification of the factor F_L in the brightness domain will be described in section 6.2.1. It can be noticed that the F_L value should have been reduced by about half. Figure 6.2 visually shows how far the F_L parameter should be modified in the graph of the log of F_L plotted against the log of $5L_A$ by the red dotted line. Yellow dotted lines indicate those prior to modification. The $\log(F_L)_{\text{-Mod}}$ was -0.17 when $F_{L\text{-Mod}}$ was 0.67. The same optimized F_L value developed based on Q was also used for M calculation.

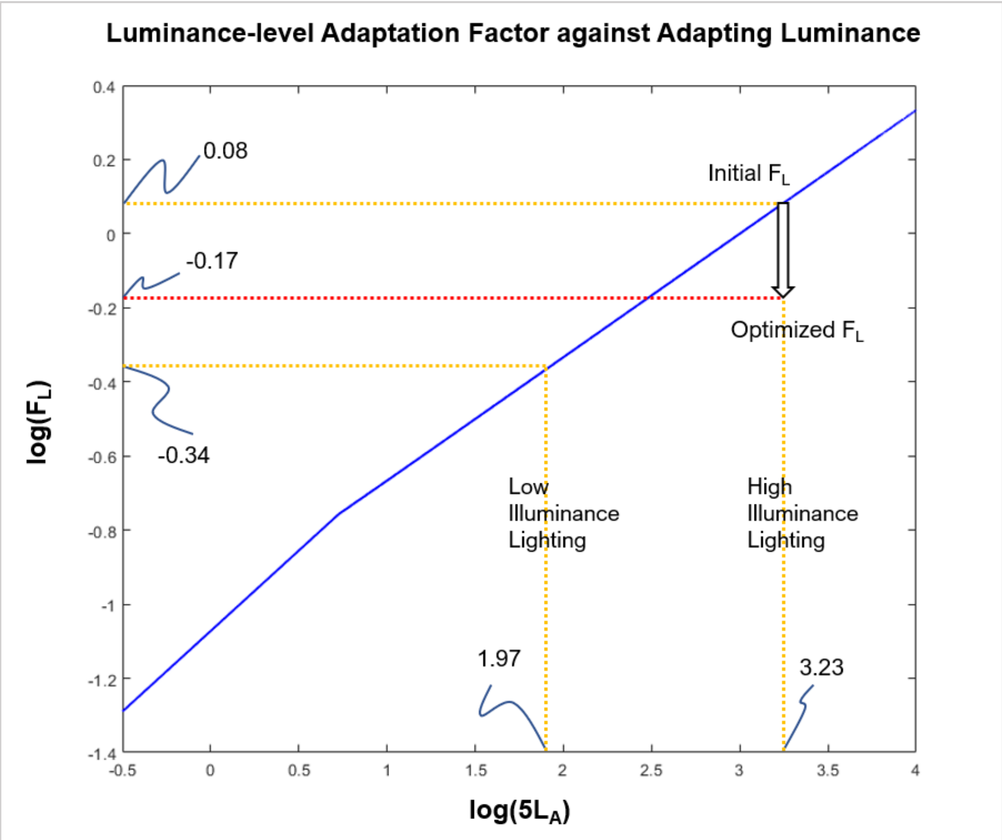


Figure 6.2 F_L against L_A and Denotation of Change Parameters for High Lum. Lighting

6.2.1 CIECAM02 Q Performance after Modification of the Factor F_L

Figure 6.3 shows brightness perception data plotted against modified CIECAM02 Q. In the figure, the x-axis denotes modified Q and the y-axis indicates brightness perception. Error bars depicting standard deviation were added along the y-axis for brightness perception data points. 45° line was drawn for a clear comparison between perception and prediction data sets. Figure 6.4 describes graphs plotting the modified Q data and the brightness perception data session by session. A linear regression line was added in every graph.

Table 6.2 shows the CV values explaining deviation between brightness perception data and modified CIECAM02 prediction Q data. For the CV analysis, Equation 4.1 was used, while x denotes brightness perception data and y denotes modified Q data. The average CV value is 7.1 and the value is far less than the previous CV value, which was ranged from 7.2 to 30.1 before the luminance-level of adaptation factor, F_L modification. Specifically, the CV value for session 2 is reduced to 5.8, which was 30.1 before modification; and the CV value for session 4 is reduced to 6.2, which was 29.7 before modification. Smaller CV value supports the rationality of lowering the value of the factor F_L in the CIECAM02 Q calculation process.

As shown in Figure 6.3, session 1 data points and session 2 data points are modified to be aligned in line after the modification of the factor F_L of session 2. Specifically, session 2 data points are placed upper right side of those of session 1. It means color patches look brighter under higher illuminance with a consistent ratio under a single lighting condition. Session 3 (local) data points and session 4 data points showed the same trend with the factor F_L of session 4 modified. The color appears to be brighter under higher illuminance with a consistent ratio under multiple lighting conditions as well. Figure 6.4 (a) and (b) show that modified Q data and brightness perception data of session 2 compared to session 1; and session 4 compared to session 3 (local) became significantly matched.

Figure 6.4 (d) shows prediction data and perception data of session 4 against session 2 are substantially matched. There was no change of the trend of the graph even after changing the F_L factor in the two sessions since the same amount of F_L change does not affect the performance of Q prediction compared to brightness perception data.

All in all, after managing the luminance level of adaptation factor F_L, 1) brightness appearance phenomenon according to illuminance level, which asserts color looks brighter under higher illuminance, was adeptly predicted both under single lighting and multiple lightings, and 2) the correlation between model prediction data and perceived brightness data according to illuminance level of lighting and the observer’s adaptation to the lighting conditions was strengthened.

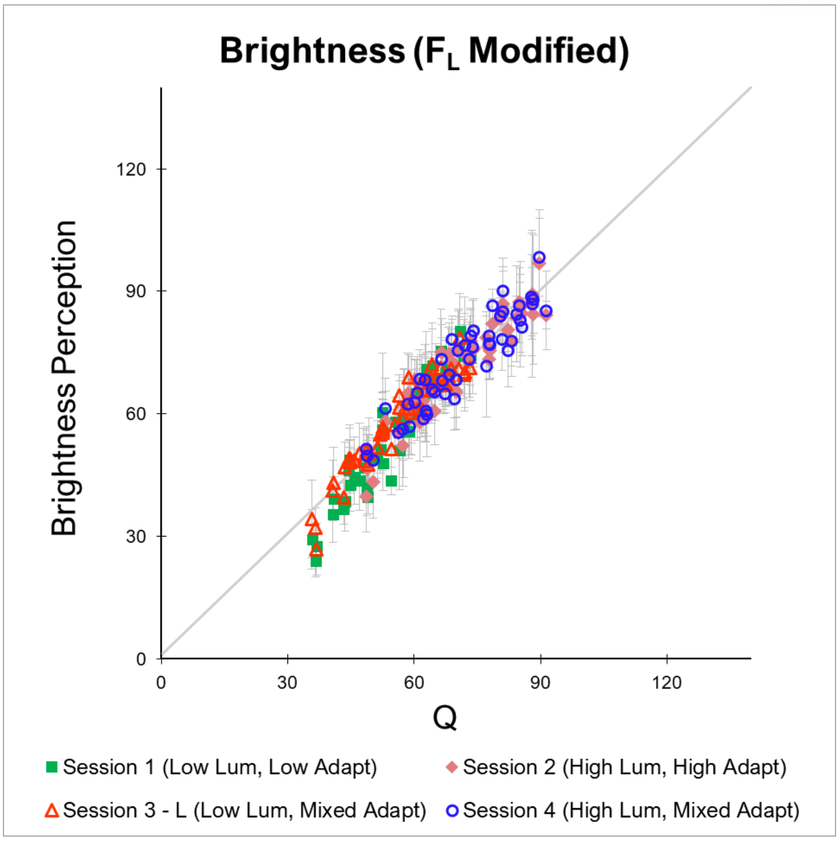
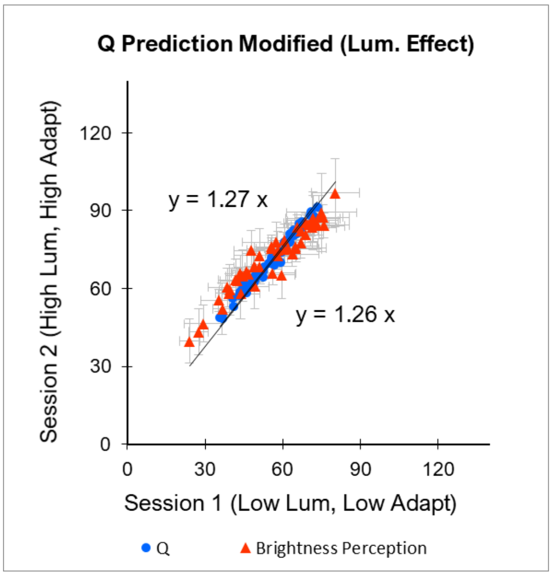


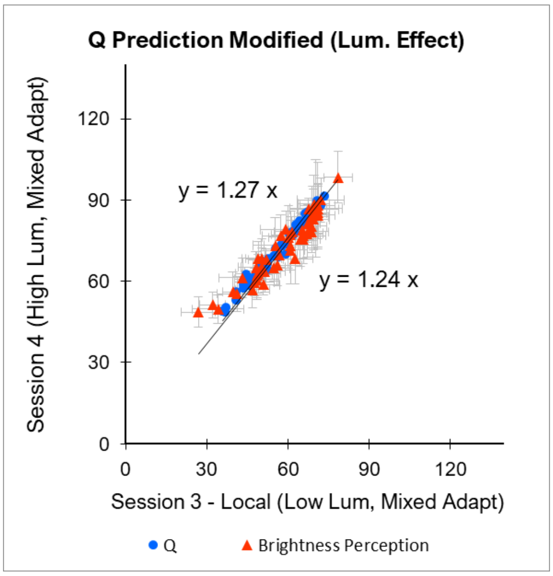
Figure 6.3 Modified CIECAM02 Q Prediction Performance

Table 6.2 CV Analysis Result between Modified CIECAM02 Q and Brightness Perception

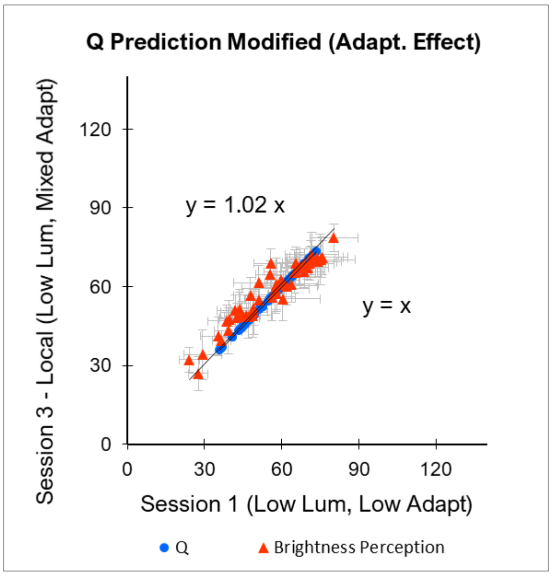
Compared Data Set		CV
Session 1	Q Modified	9.1
Session 2	Q Modified	5.8
Session 3 (Local)	Q Modified	7.2
Session 4	Q Modified	6.2
Average		7.1



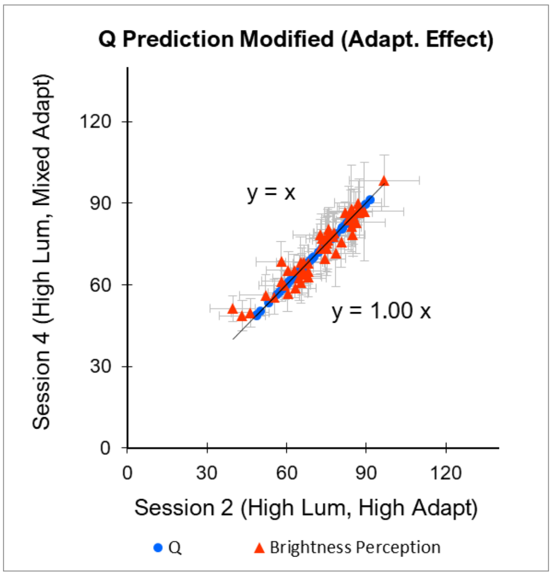
(a) Session 1 vs Session 2



(b) Session 3 (Local) vs Session 4



(c) Session 1 vs Session 3 (Local)



(d) Session 2 vs Session 4

Figure 6.4 Modified CIECAM02 Q vs Brightness Perception

6.2.2 CIECAM02 M Performance after Modification of the Factor F_L

Figure 6.5 illustrates the colorfulness perception data against modified CIECAM02 prediction M data. In the figure, the x-axis means modified M while the y-axis denotes colorfulness perception. Error bars showing the standard deviation of perception data were added to each data point along the y-axis. 45° line was added for visual comparison between perception and prediction data sets. Figure 6.6 shows the modified M and colorfulness perception data plotted session by session. A linear regression line was added to each graph.

As mentioned above, the same luminance-level adaptation factor, F_L that is optimized for Q calculation was also used for M calculation. The CV analysis was conducted, using Equation 4.1 with x denoting colorfulness perception data and y denoting modified M data in the equation. Table 6.3 says the average CV explaining the disparity between colorfulness perception data and modified CIECAM02 M data is 22.3, which was ranged from 19.7 to 23.9 before parameter modification. There was no noticeable change in the CV values.

In Figure 6.5, there was no noticeable difference between the graph of session 1 and session 3, and between the graph of session 2 and session 4.

In Figure 6.6 (a), though the model 6% underestimates M data as compared to colorfulness perception data in session 2 against session 1, the performance was improved after the luminance level of adaptation factor F_L of session 2 was modified to a smaller value. Prior to the modification, the model 10% overestimated, therefore, there was a 4% performance increment. In (b), M data of session 4 compared to session 3 (local) 18% underestimates than colorfulness perception data. There was a 16% performance decrement. Before the F_L factor modification, there was only 2% overestimation.

In Figure 6.6 (d), the adjustment of F_L in session 2 and session 4 by the same amount does not affect the performance of M prediction compared to colorfulness perception data.

In summary, after modifying the factor F_L, the correlation between CIECAM02 colorfulness prediction data and perceived colorfulness data under high illuminance lighting in a single lighting condition was strengthened. However, colorfulness prediction performance decrement was observed under high illuminance lighting in multiple lighting conditions.

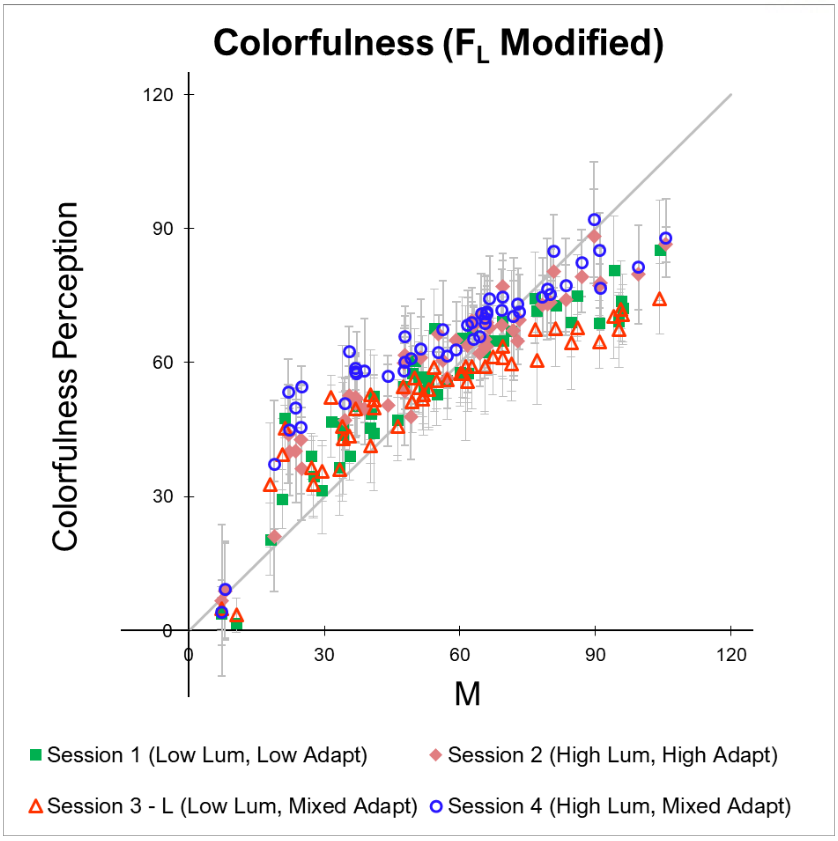
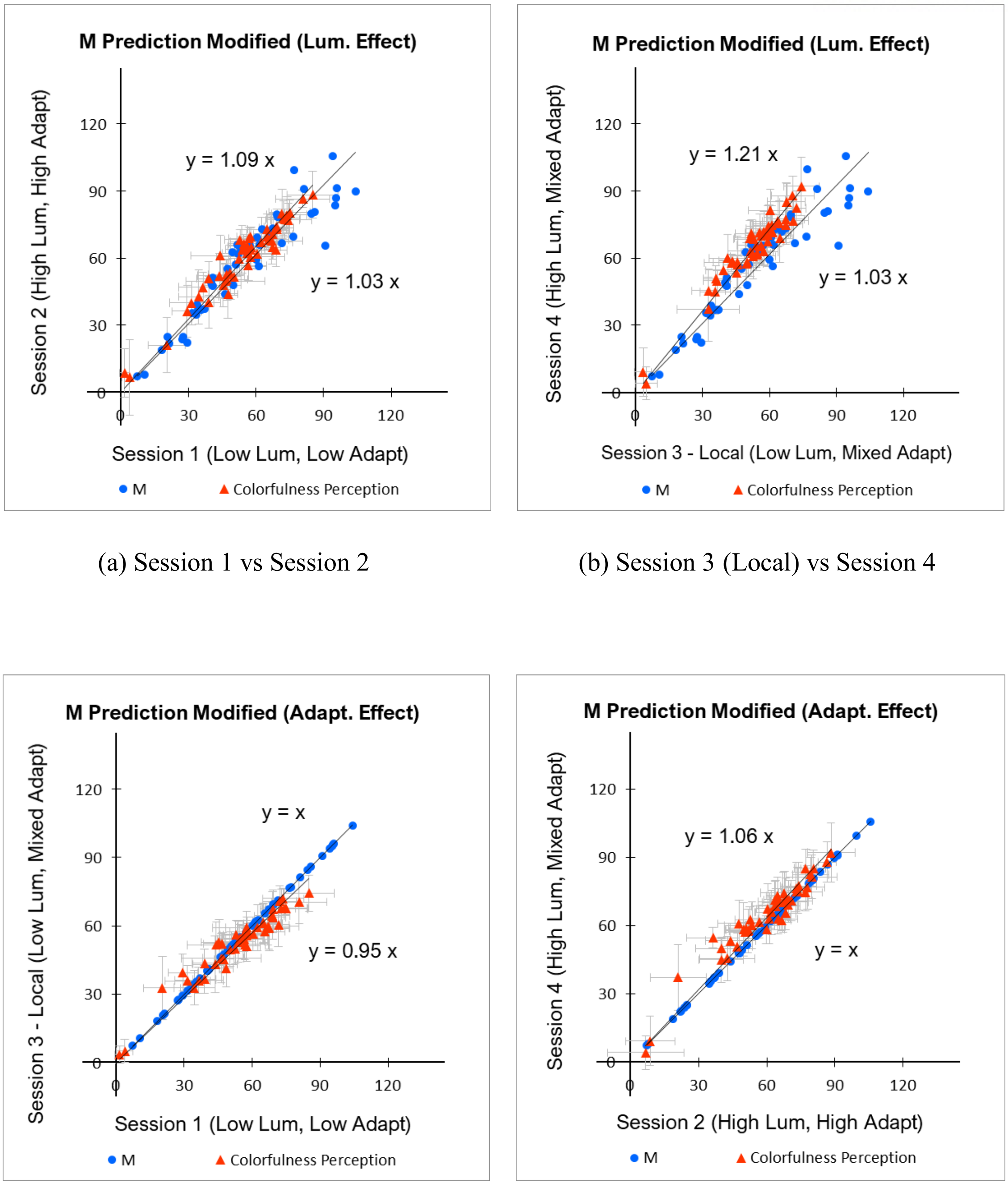


Figure 6.5 Modified CIECAM02 M Performance

Table 6.3 CV Analysis Result between Modified CIECAM02 M and Colorfulness Perception

Compared Data Set		CV
Session 1	M Modified	18.3
Session 2	M Modified	23.6
Session 3 (Local)	M Modified	23.9
Session 4	M Modified	23.5
Average		22.3



(a) Session 1 vs Session 2

(b) Session 3 (Local) vs Session 4

(c) Session 1 vs Session 3 (Local)

(d) Session 2 vs Session 4

Figure 6.6 Modified CIECAM02 M vs Colorfulness Perception

Chapter 6 Summary

In Chapter 5, it was found that CIECAM02 brightness prediction indicator Q was far overestimated as compared to the brightness perception data under higher illuminance condition both under single lighting and multiple lightings. Also, CIECAM02 colorfulness prediction indicator M was somewhat overestimated as compared to the colorfulness assessment data under higher illuminance conditions under single lighting.

The luminance-level adaptation factor F_L — which was first set as 1.20 — was optimized to 0.67 for high illuminance lighting condition, and then Q and M were recalculated. After managing the factor F_L, brightness appearance phenomenon according to illuminance level, which describes color looks brighter under higher illuminance, was markedly predicted both under single lighting and multiple lightings. In addition, the correlation between model prediction data and perceived brightness data according to the illuminance level of lighting and the observer's adaptation to the lighting conditions was strengthened. As for CIECAM02 colorfulness prediction performance after the factor F_L modification, the correlation between perceived colorfulness data under high illuminance lighting under single lighting condition was strengthened. However, performance decrement was observed under high illuminance lighting in multiple lighting conditions.

7

Conclusion

Experimental Outline

In this research, it was intended to explain color appearance phenomena in the context where observers alternately saw two light sources having largely different illuminance levels (7005 lux and 376 lux, respectively) being present at the same time.

Psychophysical experiment based on magnitude estimation technique was conducted to estimate color appearance and will be composed of four sessions according to 1) illuminance of lighting either high or low, and 2) observer's adaptation to the lighting conditions for either single lighting or multiple lightings. Seven observers who were skillfully trained for color appearance estimation participated in the experiment and evaluated the color appearance of 50 color patches in terms of hue, colorfulness and brightness throughout four sessions.

Color Visual Assessment Result

Observer performance in estimating color appearance was evaluated by the CV analysis. Observer average repeatability was 7.0, 10.6 and 13.3, and observer average reproducibility was 6.9, 10.2 and 12.7 for hue, brightness and colorfulness, respectively. Observers had provided reasonable color appearance estimation when compared to the previous study conducted by Luo et al. in 1991.

Averaged human color perception data regarding hue, brightness and colorfulness were compared across sessions, based on the illuminance of lighting and the observer's adaptation to the lighting conditions. As a result, the illuminance level where the color was actually shown (either under high illuminance or low illuminance) did not affect hue perception when observers adapted to single lighting or multiple lighting conditions. In addition, it was found that hue perception is not affected by the observer's adaptation to the lighting conditions under neither single lighting nor multiple lightings. Brightness perception is affected by the illuminance of lighting. The color looks brighter when the test color is placed under higher illuminance lighting regardless of the observer adapting to a single lighting source or to multiple lighting sources. However, whether the observer adapts to a single lighting source or to multiple lighting sources did not affect brightness perception, implying observers locally adapted to the lighting where the colors were directly shown. Lastly, as for colorfulness perception, the color looks more colorful under higher illuminance lighting either under single lighting or under multiple lightings. However, colorfulness constancy can be found regardless of the observer's adaptation to the lighting conditions, implying local adaptation has occurred (as shown in brightness perception result). The findings were partly supported by statistical analyses.

In summary, through the color appearance study under two lightings with different illuminance levels, it turned out that hue appearance was not affected by the illuminance level of lighting and the observer's adaptation to the lighting conditions. Perceived brightness and colorfulness increased under higher illuminance level but was not affected by the observer's adaptation to the lighting conditions, explaining that observers locally adapted to the lighting where the color was directly shown.

CAM Performance Evaluation

The color appearance model CIECAM02 performance was evaluated in terms of hue, brightness and colorfulness by comparing model prediction data with color perception data. CIECAM02 hue prediction data H substantially coincide with the hue perception data regardless of the illuminance level of the lighting (either high or low), and the observer's adaptation to the lighting conditions (for either single lighting or multiple lightings). As for brightness prediction performance of the CIECAM02, Q is 56% overestimated under high illuminance than under low illuminance under single lighting. Under multiple lighting conditions, Q is 58% overestimated under high illuminance than under low illuminance. Thus, the Q calculation parameter should be modified so as not to overestimate under higher illuminance. When local adaptation is assumed in mixed adaptation conditions with the color shown under low illuminance, the Q prediction performance is increased by 18 – 39%. Regarding the colorfulness prediction performance of the model, M is 10% overestimated under high illuminance than under low illuminance under single lighting. Thus, the M calculation parameter should be modified so as not to overestimate under higher illuminance. When local adaptation is assumed in mixed adaptation conditions with the color shown under low illuminance, the M prediction performance is increased by 44 – 88%. All findings were supported by the CV values calculated between color perception data and model prediction data.

The luminance-level adaptation factor F_L — which was first set as 1.20 — was optimized to 0.67 for high illuminance lighting conditions in order not to overestimate Q and M, and then Q and M were recalculated. After managing the factor F_L, brightness appearance phenomenon according to illuminance level (which describes how a color looks brighter under higher illuminance) were markedly predicted both under single lighting and multiple lightings. In addition, the correlation between model prediction data and perceived brightness data according to the illuminance level of lighting and the observer's adaptation to the lighting conditions for either single lighting or multiple lightings was strengthened. As for CIECAM02 colorfulness prediction performance after the factor F_L modification, the correlation between perceived colorfulness data under high illuminance lighting under single lighting condition was strengthened. However, performance decrement was observed under high illuminance lighting in multiple lighting conditions.

To sum up, it was found that the CIECAM02 H significantly predicted hue appearance regardless of the illuminance level of lighting and the observer's adaptation to the lighting conditions. However, the CIECAM02 Q and the CIECAM02 M were overestimated under high illuminance lighting. The modification of the luminance-level adaptation factor, F_L — by lowering the value of it from 1.20 to 0.67 — helped the model not to overestimate Q and M.

Methodological Limitation

The psychophysical method used for color appearance evaluation in this research was magnitude estimation. The method could have brought several limitations to the study. First, in brightness and colorfulness domains, when comparing the visual perception data of session by session or comparing the visual perception data and the CIECAM02 model prediction data, it was assumed that the regression line of the data points in each graph passed the origin. Because in the domain of brightness, the brightness of the observer's imaginary black is zero, and in the domain of colorfulness, the colorfulness of an achromatic color is zero. However, when the regression line was set to have an intercept, the regression line represented data points 10.3% better when comparing brightness perception data session by session, and 2.5% better for colorfulness. When comparing CIECAM02 Q data with brightness perception data, the regression line explained the data points 1.8% better, and 30.5% better when comparing CIECAM02 M data to colorfulness perception data. This could be interpreted as a methodological limitation in which the perception tendency was shifted because observers had difficulty setting the brightness of imaginary black or colorfulness of achromatic color to zero.

Second, in the brightness and colorfulness domains, it was assumed that perception data and CIECAM02 model prediction data points had a linear relationship. In the brightness domain, linear regression lines best represent the correlation between CIECAM02 Q data and brightness perception data as assumed. However, in the colorfulness domain, when the correlation between CIECAM02 M data and colorfulness perception data was described as a logarithmic regression line instead of a linear regression line, the logarithmic regression line represented the data 42% better. This resulted in the observer's reluctance to report extreme values when performing colorfulness estimation, resulting in sluggish trends in observer data points as the colorfulness increased. This is also a methodological limitation of magnitude estimation.

Third, there were some concerns about the reference color patch used as an anchor in the magnitude estimation of this study. 1) When an observer evaluated a test color, the observer should have relatively evaluated the test color based on the reference patch, but it also could have been possible that the observer evaluated based on the reflectance of the test color itself. 2) In this experiment, the brightness and colorfulness of the reference color patches of session 2 and session 3 were assigned based on those of the reference color patch in session 1. At this time, the act of assigning a number to the brightness and colorfulness of the reference color patches itself might have determined the entire trend of the color visual assessment data. 3) When setting the brightness and colorfulness values of the reference color patches of session 2 and session 3, observers were required to remember the visual sense of brightness and colorfulness of the reference color patch of session 1 for 2 minutes. Given that human working memory (a.k.a short-term memory) is 15-30 seconds (Goldstein, 2011), the visual sense of the reference patch for session 1 went to long-term memory domain so that the visual color assessment can be biased.

Fourth, when evaluating a test color patch, the test color stimulus distribution given to each observer could have affected the overall color visual assessment result, as the perception for the test color patch could be influenced by the test color patch presented previously. In fact, observers sometimes asked the experimenter what they reported about the previous patch. A qualitative study will be conducted on whether stimulus distribution affected color evaluation in this experiment as a future study. All observers evaluated the same 50 randomly ordered patches in this research. In a further study, it might be helpful to conduct an experiment in which each observer evaluates a different set of color patches.

Further Study

Through this research, color appearance under two lightings having 19 times different luminance levels was investigated. In everyday life, the color is often shown under the interaction of multiple lightings. It is common to see a scene having two or more light sources together, or to look at an object that is shadowed by other objects. Given the current color appearance models that have been developed based on a single lighting source, it is necessary to study color appearance under dynamic lighting conditions described above. However, there has been little research on color appearance under those conditions so far. Therefore, this study is meaningful in that it obtained the perception data of color appearance in multiple lighting conditions having different illuminance levels.

The results described above are based on color appearance perception when there are only two lightings having 19 times the illuminance difference. Therefore, it cannot be firmly concluded that these phenomena are actually common color appearances in multiple lighting environments. Therefore, it is necessary to conduct additional color appearance estimation research in multiple lighting conditions that possess more diverse illuminance level differences or have different configurations of lightings. Also, as described above, efforts will be needed to devise experimental methods that overcome the limitations of the magnitude estimation method used in this study.

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Appendix

Appendix 1. Experimental Instruction for Observers

Color Appearance Perception Experiment

[Research Objective]

This research is to investigate how observers perceive hue, brightness, and colorfulness of the color patches, depending on the observer's adaptation environment when multiple lightings exist at the same time.

[Color Appearance Estimation Method]

The followings are the definitions of hue, colorfulness and brightness as defined by CIE.

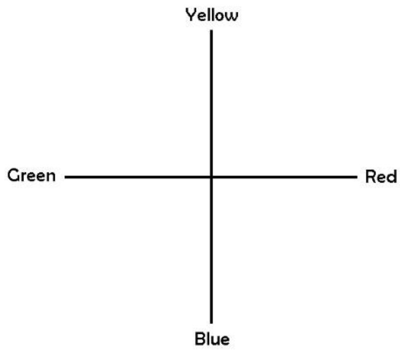
Hue is the attribute of a visual sensation according to which an area appears to be similar to one, or proportions of two, of the perceived colors red, yellow, green, and blue.

Colorfulness is the attribute of a visual sensation according to which an area appears to exhibit more or less of its own hue.

Brightness is an attribute of a visual perception according to which an area appears to emit, or reflect, more or less light.

Hue Estimation

The hue estimation is a way to evaluate how the four unique hues, red, green, blue and yellow, appear to be mixed. Red and green are located at both ends of the x-axis, and yellow and blue are located at both ends of the y-axis, as shown on the right. Therefore, the two colors at both ends cannot be mixed. You are going to evaluate which hues are mixed in what proportion.



First, check whether the hue can be recognized in the test color patch. If you cannot tell any hue (achromatic) in each color patch, you can say 'Neutral'. If you recognize the hue, then determine which of the four unique hues seems closest to the test color patch. Next, consider whether the test colors seem to be mixed with different hues, and then determine in what proportion the two hues you selected are mixed. For example, orange would be estimated as 60% Yellow and 40% Red.

Colorfulness Estimation

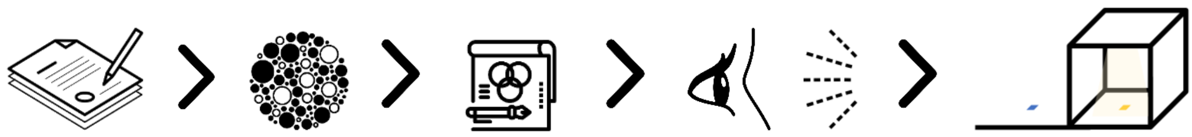
Neutral color has no colorfulness and is expressed as 0. There is no maximum value for colorfulness. The colorfulness estimation is a way to assign a relative number to the colorfulness of the test color based on when the colorfulness of a reference patch is a certain number (the number assigned varies from session to session).

Brightness Estimation

The brightness of the reference patch is a certain number (the number assigned varies from session to session), and the brightness of the ideal black is zero. Based on this, you can evaluate the brightness of the test color in number. There is no maximum value for brightness.

[Experimental Procedure]

There are four experimental sessions, one session per day and a total of four days. One session will take about 40 minutes. The experimental process is shown below. Except for the first day, only 4-5 will proceed.



1. Read experimental instruction and fill out the experiment agreement
2. Proceed Ishihara blind test
3. Learn color appearance terminologies and color scaling
4. Adapt to the experimental environment
5. Evaluate the color appearance of the color patches

[Participant Info]

* Your info will never be used for any purpose other than for the experiment.

1. Name:
2. Sex: M / F
3. Do you have any kind of color-blind or color amblyopia: Yes / No

Thank you for your participation :)

Name: __________________ (Sign)

Appendix 2. The Absolute XYZ of Experimental Stimuli Measured by Spectroradiometer (CS-2000, Minolta) under Actual Experimental Scene

	High Illuminance Lighting			Low Illuminance Lighting		
	X	Y	Z	X	Y	Z
S 0520-R40B	1293.4	1293.6	1220.2	73.8	72.9	74.7
S 0540-B30G	820.8	1127.4	1168.3	46.7	60.5	66.0
S 0550-Y10R	1364.8	1383.6	398.5	75.1	84.4	21.2
S 0550-Y70R	1125.1	898.9	394.7	59.3	48.5	21.9
S 0560-G40Y	821.9	1129.8	331.8	47.8	66.9	17.0
S 0560-G90Y	1075.4	1228.9	250.0	66.2	78.6	13.4
S 0575-G60Y	805.2	1081.8	165.9	50.3	68.9	7.8
S 0570-G80Y	1042.4	1262.3	208.5	60.4	74.7	10.0
S 0570-Y60R	974.2	716.0	199.1	51.5	39.0	10.0
S 0580-G30Y	498.4	845.1	171.3	30.0	50.3	7.2
S 0580-Y	1149.9	1216.9	129.3	68.5	79.5	5.3
S 0580-Y90R	664.3	383.3	112.1	37.0	21.7	5.9
S 0585-Y40R	819.0	593.3	75.0	46.7	36.4	3.7
S 1030-Y40R	1136.6	1074.0	505.0	61.9	60.4	28.5
S 1040-Y90R	1026.2	849.0	529.1	53.9	45.4	29.6
S 1055-B90G	492.5	832.0	591.4	28.1	44.4	31.8
S 1060-B	453.4	618.6	1019.4	25.8	31.8	59.6
S 1060-Y40R	875.7	712.5	192.4	49.5	43.0	10.6
S 1070-G10Y	354.4	674.9	270.5	21.2	37.5	14.0
S 1075-G70Y	809.2	1017.5	144.9	46.4	62.1	6.1
S 1575-R10B	544.7	305.0	151.2	20.7	11.9	6.7
S 2020-G20Y	728.5	903.5	648.3	42.2	52.7	36.3
S 2020-G50Y	778.8	918.1	562.3	45.5	55.3	31.6
S 2040-B90G	460.2	688.0	514.5	27.6	39.3	30.5
S 2040-R50B	581.3	523.3	671.8	35.5	31.2	44.7
S 2060-B50G	283.1	499.8	522.6	16.4	25.7	29.2
S 2060-R30B	550.1	357.5	373.6	27.4	17.8	21.9
S 2065-R90B	270.1	319.8	771.1	14.0	14.5	42.9
S 2070-G50Y	405.4	551.6	110.2	25.8	40.6	4.8
S 2075-G20Y	216.3	423.6	108.0	13.9	27.0	4.9

S 2502-B	815.6	907.5	791.8	47.6	52.2	48.7
S 2555-B30G	296.0	476.7	584.6	16.9	24.2	32.5
S 2570-Y30R	596.7	488.8	91.0	31.0	27.5	3.8
S 3005-Y20R	747.3	804.0	595.5	41.1	44.7	32.9
S 3020-Y80R	650.0	610.4	417.3	35.6	33.8	23.6
S 3050-B20G	250.6	377.9	484.3	13.9	19.1	28.2
S 3050-R60B	307.5	266.9	500.7	18.0	14.6	33.3
S 3050-Y80R	450.0	332.0	152.4	24.1	17.9	8.0
S 3060-B10G	201.3	302.7	494.3	10.2	13.5	26.8
S 3060-B90G	171.0	345.4	228.8	7.8	15.3	10.4
S 3060-R	337.5	212.6	101.5	14.4	8.7	3.7
S 3060-R70B	215.3	193.1	502.8	12.3	9.9	32.6
S 4020-G70Y	437.1	507.5	263.3	27.8	32.9	16.7
S 4030-B	283.3	356.1	438.7	16.5	19.5	27.6
S 4040-B80G	216.0	348.8	283.6	11.3	17.7	14.7
S 4020-R50B	483.9	476.4	521.5	25.6	24.6	29.4
S 5030-R30B	296.0	241.5	238.7	14.5	11.7	12.8
S 5040-R70B	149.3	142.7	295.6	7.2	6.1	17.1
S 6030-B10G	125.0	165.1	209.4	5.8	7.2	11.3
S 6030-Y90R	167.5	130.7	68.6	8.3	6.2	3.2
S 0500-N (White)	1546.5	1680.6	1420.9	86.0	93.1	82.4
S 2040-Y90R (Ref.)	743.0	604.4	358.5	38.4	31.2	20.4
S 1070-R20B (Ref.)	703.9	429.9	319.9	33.2	20.4	17.9
S 3555-B80G (Ref.)	177.4	338.1	261.5	7.8	13.8	12.1
Grey (Bg. High)	638.3	701.6	585.5	32.0	34.9	28.5

Appendix 3. Color Appearance Visual Assessment Data (Average of All Observers)

	Session 1		
	Hue	Brightness	Colorfulness
S 0520-R40B	359.0	80.3	20.4
S 0540-B30G	295.0	75.4	44.1
S 0550-Y10R	101.4	73.6	57.6
S 0550-Y70R	34.3	68.7	53.9
S 0560-G40Y	174.3	71.6	67.0
S 0560-G90Y	97.0	74.0	74.4
S 0570-G80Y	115.4	75.9	75.0
S 0570-Y60R	37.1	63.7	69.3
S 0575-G60Y	146.9	71.4	73.7
S 0580-G30Y	177.9	65.0	72.1
S 0580-Y	100.7	75.0	85.1
S 0580-Y90R	287.9	60.4	80.7
S 0585-Y40R	47.9	61.9	72.9
S 1030-Y40R	66.9	70.0	46.4
S 1030-Y40R	55.7	67.7	46.4
S 1040-Y90R	179.6	70.9	45.4
S 1055-B90G	217.9	65.0	56.0
S 1060-B	296.1	58.0	65.4
S 1060-Y40R	47.1	60.7	56.0
S 1070-G10Y	182.1	58.0	64.9
S 1075-G70Y	150.0	66.9	69.3
S 1575-R10B	334.3	46.1	71.6
S 1575-R10B	334.0	43.0	66.7
S 2020-G20Y	184.4	65.6	34.6
S 2020-G50Y	179.3	68.7	31.4
S 2040-B90G	228.6	55.7	48.6
S 2040-R50B	350.0	55.6	50.3
S 2060-B50G	217.6	51.1	56.9
S 2060-R30B	370.0	49.1	67.3
S 2065-R90B	299.3	48.7	65.0

S 2070-G50Y	172.9	59.6	68.9
S 2075-G20Y	193.6	56.1	69.0
S 2502-B	306.0	71.7	3.9
S 2555-B30G	267.1	49.1	57.6
S 2555-B30G	271.4	49.4	56.9
S 2570-Y30R	47.9	43.6	57.6
S 3005-Y20R	68.3	67.1	1.6
S 3020-Y80R	120.7	57.6	29.4
S 3020-Y80R	178.1	54.9	32.6
S 3050-B20G	276.1	46.9	54.6
S 3050-B20G	279.0	45.0	55.1
S 3050-R60B	346.4	44.6	60.4
S 3050-Y80R	66.0	39.6	56.6
S 3060-B10G	278.3	38.6	52.9
S 3060-B90G	205.7	42.6	67.6
S 3060-R	339.9	35.3	62.4
S 3060-R70B	309.3	39.3	57.9
S 4020-G70Y	176.0	51.0	39.0
S 4020-R50B	346.4	47.9	47.6
S 4030-B	296.1	41.9	43.7
S 4040-B80G	208.6	43.7	52.6
S 5030-R30B	351.4	36.6	46.9
S 5040-R70B	306.1	29.3	47.1
S 6030-B10G	285.4	27.6	36.4
S 6030-Y90R	125.7	24.0	39.0

	Session 2		
	Hue	Brightness	Colorfulness
S 0520-R40B	375.7	96.9	21.0
S 0540-B30G	292.6	87.4	61.1
S 0550-Y10R	90.0	84.1	60.4
S 0550-Y70R	28.6	80.6	63.9
S 0560-G40Y	170.7	86.1	67.7
S 0560-G90Y	104.7	87.4	77.0
S 0570-G80Y	122.9	84.4	80.4
S 0570-Y60R	45.0	73.3	73.0
S 0575-G60Y	142.4	83.4	79.3
S 0580-G30Y	172.1	75.6	77.9
S 0580-Y	98.6	89.3	88.3
S 0580-Y90R	233.1	75.1	86.4
S 0585-Y40R	45.7	75.4	77.1
S 1030-Y40R	53.6	84.6	49.7
S 1030-Y40R	67.1	80.9	51.9
S 1040-Y90R	180.7	85.0	47.9
S 1055-B90G	227.4	76.1	62.1
S 1060-B	293.9	74.6	68.3
S 1060-Y40R	49.3	78.6	65.3
S 1070-G10Y	186.4	72.7	72.9
S 1075-G70Y	149.3	77.6	74.0
S 1575-R10B	339.7	66.6	79.7
S 1575-R10B	341.4	66.0	78.3
S 2020-G20Y	205.0	83.6	42.7
S 2020-G50Y	182.1	85.3	40.0
S 2040-B90G	225.0	76.0	53.6
S 2040-R50B	349.3	75.3	51.7
S 2060-B50G	245.0	68.3	68.9
S 2060-R30B	373.1	60.7	64.7
S 2065-R90B	295.7	68.3	69.6
S 2070-G50Y	167.9	65.3	63.6
S 2075-G20Y	184.0	65.9	73.6
S 2502-B	300.0	87.0	6.7

S 2555-B30G	267.1	68.3	69.4
S 2555-B30G	257.1	69.4	66.9
S 2570-Y30R	44.3	65.9	63.7
S 3005-Y20R	80.0	82.0	8.7
S 3020-Y80R	125.7	77.9	36.3
S 3020-Y80R	124.3	78.6	42.7
S 3050-B20G	268.6	65.4	66.4
S 3050-B20G	276.4	64.9	68.1
S 3050-R60B	345.7	64.9	61.7
S 3050-Y80R	20.0	59.3	56.6
S 3060-B10G	287.1	60.4	68.1
S 3060-B90G	204.0	62.9	70.7
S 3060-R	342.1	55.4	67.1
S 3060-R70B	312.1	58.1	65.0
S 4020-G70Y	175.7	72.7	40.1
S 4020-R50B	347.1	74.6	44.0
S 4030-B	293.6	63.3	52.1
S 4040-B80G	210.0	58.0	59.9
S 5030-R30B	360.7	52.1	52.6
S 5040-R70B	305.0	46.4	50.4
S 6030-B10G	269.3	43.3	47.0
S 6030-Y90R	68.6	39.7	50.9

	Session 3		
	Hue	Brightness	Colorfulness
S 0520-R40B	362.1	78.6	32.6
S 0540-B30G	293.6	71.1	51.6
S 0550-Y10R	100.7	71.1	59.1
S 0550-Y70R	34.3	65.7	52.9
S 0560-G40Y	167.9	69.4	59.7
S 0560-G90Y	110.7	69.6	67.4
S 0570-G80Y	114.6	71.0	67.7
S 0570-Y60R	40.0	61.0	63.7
S 0575-G60Y	156.4	71.0	72.0
S 0580-G30Y	170.7	65.7	70.7
S 0580-Y	88.3	70.3	74.3
S 0580-Y90R	230.3	55.3	70.4
S 0585-Y40R	45.0	60.1	67.6
S 1030-Y40R	59.3	67.3	45.7
S 1030-Y40R	61.4	70.3	47.1
S 1040-Y90R	191.4	68.7	52.7
S 1055-B90G	222.9	65.4	54.0
S 1060-B	295.0	57.3	57.4
S 1060-Y40R	53.6	61.0	56.1
S 1070-G10Y	180.0	61.0	61.0
S 1075-G70Y	155.7	67.0	67.3
S 1575-R10B	340.0	49.0	60.4
S 1575-R10B	334.3	48.6	59.1
S 2020-G20Y	191.4	68.7	32.7
S 2020-G50Y	178.6	69.0	35.7
S 2040-B90G	197.1	68.9	41.3
S 2040-R50B	350.4	64.6	49.6
S 2060-B50G	257.9	54.9	51.9
S 2060-R30B	371.4	50.3	59.1
S 2065-R90B	297.9	49.0	61.3
S 2070-G50Y	169.3	62.6	64.6
S 2075-G20Y	179.3	56.0	64.4
S 2502-B	300.0	72.1	4.9

S 2555-B30G	272.1	51.9	51.1
S 2555-B30G	275.7	52.1	54.1
S 2570-Y30R	50.0	51.4	55.7
S 3005-Y20R	130.0	67.6	3.4
S 3020-Y80R	122.7	59.3	39.4
S 3020-Y80R	120.3	60.6	39.1
S 3050-B20G	272.9	48.4	54.6
S 3050-B20G	281.1	49.3	52.9
S 3050-R60B	345.3	48.6	56.4
S 3050-Y80R	74.3	47.6	54.3
S 3060-B10G	289.3	46.9	56.0
S 3060-B90G	191.1	48.1	58.9
S 3060-R	174.7	41.1	59.1
S 3060-R70B	317.1	43.1	57.4
S 4020-G70Y	172.1	61.4	36.4
S 4020-R50B	345.0	56.7	45.3
S 4030-B	295.0	50.9	43.0
S 4040-B80G	207.9	50.3	49.9
S 5030-R30B	355.0	39.6	52.1
S 5040-R70B	314.6	34.1	45.7
S 6030-B10G	295.7	26.9	36.0
S 6030-Y90R	126.4	32.1	43.6

	Session 4		
	Hue	Brightness	Colorfulness
S 0520-R40B	372.3	98.3	37.1
S 0540-B30G	290.0	86.6	63.0
S 0550-Y10R	83.6	85.3	67.3
S 0550-Y70R	35.0	75.6	68.4
S 0560-G40Y	167.1	82.9	74.3
S 0560-G90Y	104.3	88.6	74.6
S 0570-G80Y	104.0	88.0	85.0
S 0570-Y60R	42.1	77.1	76.4
S 0575-G60Y	145.7	84.4	82.3
S 0580-G30Y	171.4	76.9	76.7
S 0580-Y	99.3	86.9	92.0
S 0580-Y90R	232.9	73.3	87.9
S 0585-Y40R	42.1	76.3	85.1
S 1030-Y40R	54.3	81.3	58.1
S 1030-Y40R	52.9	82.0	60.1
S 1040-Y90R	125.7	78.3	60.9
S 1055-B90G	228.6	79.0	65.7
S 1060-B	292.1	76.7	71.7
S 1060-Y40R	49.9	71.6	70.0
S 1070-G10Y	179.3	73.3	74.7
S 1075-G70Y	142.4	77.7	77.3
S 1575-R10B	339.3	68.3	81.3
S 1575-R10B	339.0	66.4	81.9
S 2020-G20Y	206.4	83.9	45.4
S 2020-G50Y	172.1	85.0	44.9
S 2040-B90G	227.1	80.3	60.0
S 2040-R50B	354.3	75.4	57.4
S 2060-B50G	242.9	64.9	71.0
S 2060-R30B	325.0	65.3	73.1
S 2065-R90B	296.9	62.9	71.3
S 2070-G50Y	165.0	68.3	68.7
S 2075-G20Y	178.6	66.0	75.3
S 2502-B	290.0	90.0	4.0

S 2555-B30G	276.4	68.0	69.0
S 2555-B30G	264.3	64.0	68.3
S 2570-Y30R	49.3	63.7	71.3
S 3005-Y20R	145.0	86.6	9.1
S 3020-Y80R	122.9	79.1	54.6
S 3020-Y80R	124.3	74.6	51.1
S 3050-B20G	275.7	60.7	62.3
S 3050-B20G	270.0	60.3	63.4
S 3050-R60B	347.1	62.4	65.7
S 3050-Y80R	73.6	59.7	61.4
S 3060-B10G	279.3	56.9	65.3
S 3060-B90G	196.4	65.1	70.9
S 3060-R	342.1	55.4	70.3
S 3060-R70B	325.0	61.3	62.9
S 4020-G70Y	170.7	78.3	49.9
S 4020-R50B	347.9	69.6	53.3
S 4030-B	273.6	58.7	57.9
S 4040-B80G	201.0	68.4	58.1
S 5030-R30B	361.4	56.1	62.4
S 5040-R70B	317.1	49.7	57.0
S 6030-B10G	271.4	48.6	50.7
S 6030-Y90R	125.7	51.3	58.7

EPILOGUE

안녕하세요 :) 유니스트 색채연구실의 재간둥이 석사 홍예진입니다. 이젠 '석사과정생'이 아닌 '석사'라고 조심스레 명명해도 되겠지요..? 생각해보니 무려 4학년 여름학기부터 단청을 시작으로 색채연구실에 몸담아왔네요. 인복 하나는 정말 좋은 저는 천사 같으신 컬러계의 핵심 (실제로 휴대폰에 이렇게 저장된..) 곽영신 교수님을 만났고, 정말 멋있는 선배들, 나라사랑 동기사랑 가람이, 귀여운 후배 누룽지와 함께 즐거운 석사생활을 할 수 있었습니다. 2년이 정말 후다닥 지나가서 적잖이 놀랐습니다..^^; 제가 즐거이 석사 생활을 할 수 있도록 도와주신 교수님과 연구실 식구들 정말 사랑합니다 ♡

곽영신 교수님, 학부 때 감성공학 수업 때 교수님을 처음 뵈었는데, 그때나 지금이나 한결같이 학업 이상의 부분에서도 고민 잘 들어주시고 제가 허접한 논문을 들고가도, 쉬운 개념도 이해를 잘 못 하고 어영부영하고 있을 때도 놓지 않고 끝까지 친절하게 지도해주셔서 정말 감사했습니다. 교수님은 최고의 멘토십니다. 정말 멋지십니다. 존경합니다, 교수님.

권오상 교수님, 교수님 바쁘신 와중에 제 논문을 심사해주셔서 감사합니다. 제가 미처 생각지 못했던 부분들 예리하게 짚어주셔서 정말 감사했습니다. 인간공학개론 때 TA로서 교수님의 2주 남짓 수업을 들었는데 정말 재밌었습니다. 감각과지각 수업을 못 들은 것이 정말 아쉬웠습니다. 교수님은 저의 second favorite 교수님이십니다!

황지수 박사님, 저의 제2의 지도자이신 박사님! 대전에서부터 오셔서 논문을 심사해주셔서 감사합니다. 2년 남짓 과제를 함께 하며 박사님께 실험 방법론과 데이터 분석방법을 정말 많이 배웠습니다. 표준연에서 한 달 동안 연구보조를 할 때, 제가 많이 답답하셨을 텐데도 하나하나 차근차근 알려주시고 요가도 데려가 주시고 정말 감사했습니다.

백예슬 박사님 (백언니), 우리 연구실 reference white 백언니! 부족한 후배 어여삐 여겨주시고 제가 고민 털어놓을 때마다 공감 잘해주셔서 너무 감사해요. 주말이고 공휴일이고 심심하다고 찡찡거릴 때도 다 받아주셔서 감사합니다. 언니가 가는 길을 항상 응원할게요.

오세민 예비박사님 (사리몽오빠), 오빠 저는 알아요, 오빠가 컬러랩의 갓-벽한 구심점이라는 것을! 2년 동안 오빠한테 질문을 제일 많이 했던 것 같아요. 귀찮아하지 않고 친절하게 여러 번 설명해주셔서 정말 감사합니다. 제 별명 약 50개 지어주신 것도 감사해요.

하혜영 예비박사님 (하언니), 고명파 우두머리 혜영언니! 둘이 밥 먹을 때마다 고민 열렬히 들어주시고 조언해주셔서 감사합니다. 언니의 투명하고 착한 심성이 빛을 발하길 바랍니다. 올해는 아프지 마세요! 항상 자기계발 열심히 하는 언니가 멋있어요.

하나뿐인 동기 성가람, 너 같은 동기가 있어서 다행이야. 2년 동안 그냥 다 고마웠어! 너가 없었으면 곤란했겠어. 나는 가람이가 꼭 잘됐으면 좋겠어. 졸업여행 얼른 가자 못 기다리겠어. 여기서 못다 한 얘기 육성으로 들려줄게. 알라뷰!

고민정, 자기가 센 줄 알지만 사실은 세상 여린 백설공주 밀키야! 내가 어떤 말을 하던 무조건 내편이어줘서 고마워. 너 같은 공감봇은 처음이야. 배고파할 때마다 간식 준 것도 고마워. 참고로 나도 맨날 니편이야.

윤선영, 나 웃음 장벽이 정말 높은데 그 장벽을 와르르 무너뜨린 끼쟁이 윤으야! 지금이라도 늦지 않았어. 데뷔하자. 나를 매일 빵터지게 해줘서 고마워. 가끔 자다가도 니가 유리컵 닦는 소리 흉내 내는 게 생각나.

박현희, 사실은 흥부자 방연아! 나는 들었어. 너가 미국 출장 때 숙소에서 몰래 노래 부른 것을. 너는 흥부자야. 내가 방연이 귀여워서 정말 많이 놀리는데 초연하게 받아들여 줘서 고마워. 너가 제일 귀여워.

6년 동안 숨구멍 아주아주 크게 만들어 준 언플러그드 친구들, 인간공학 전공하면서 건진 보물 같은 친구들 은영, 여정, 민수, 수행평가하면서 난리치던 애들이 직장 얘기하는 게 충격인 8반 일동 다들 고맙고 사랑해!

Marisa, it's almost been 10 years you and me being friends. Thank you for cheering me up all the time though we cannot meet often. I always cheer for you too. Also, thank you for correcting my English for this paper.

마지막으로 내가 하는 것, 내가 가는 길 무조건 믿고 응원해주는 사랑하는 우리 가족들 내가 평생 행복하게 해줄게! 너무 고맙고 사랑합니다! 귀여운 코코도 사랑해!